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ORIGINAL RESEARCH

Reconciling Product Flexibility with Cost, Delivery, and Quality: The Importance of Bundling Mass Customization Practices

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Abstract *Reconciling product flexibility with cost, delivery, and quality is an ambidextrous organizational capability known as mass customization capability. This study focuses on how this capability is affected by the joint implementation of three organizational practices—knowledge absorption from customers, product modularity, and online sales configurator use—that directly correspond to the three fundamental building blocks of mass customization identified by prior, influential research. By drawing upon a central tenet of resource orchestration theory, the fit-as-covariation perspective, and prior mass customization research, we conceptually develop the hypothesis that the fit-as-covariation of these practices has a stronger positive association with mass customization capability than the same practices implemented in isolation. This hypothesis was tested using covariance-based structural equation modeling and survey data from 213 manufacturing plants in three industries across 16 countries. Our results support the hypothesis, showing that the joint effect of these practices explains substantially more mass customization capability variation (41.9%) than their isolated effects (13.9%). This amount of variation indicates an effect size that is greater than that reported by most previous survey-based studies on the antecedents of this capability. Theoretically, this paper adds to the relatively limited body of knowledge on the relationships among the enablers of mass customization by highlighting the benefits of a holistic approach in the implementation of the three practices under investigation. Pragmatically, this study helps companies create flexible systems that are able to provide customized products without compromising cost, delivery, or quality.*

Keywords Flexibility · Knowledge absorption from customers · Mass customization · Product configuration · Product modularity · Resource orchestration

Abbreviations

AVE	Average variance extracted
CB-SEM	Covariance-based structural equation modeling
CFA	Confirmatory factor analysis
CFI	Comparative fit index
CR	Composite reliability
df	Degrees of freedom
HPM	High-performance manufacturing
IFI	Incremental fit index
IRAC	Inter-rater agreement coefficient
IT	Information technology
KAfC	Knowledge absorption from customers
MCC	Mass customization capability
OSCU	Online sales configurator use
PM	Product modularity

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RMSEA	Root-mean-square error of approximation
ROT	Resource orchestration theory
TLI	Tucker–Lewis index

Introduction

Flexibility has long been recognized as a critical factor in enabling companies to navigate rapidly changing socioeconomic landscapes (Singh et al., 2021). The need for flexibility has intensified in today's business environment, as organizations must adapt to increasingly complex and dynamic markets while transitioning toward sustainable production and consumption paradigms (Basile et al., 2024; D'Adamo et al., 2023; Sushil, 2018).

Research on flexibility is grounded in the manufacturing/operations strategy literature, which has examined the role of flexibility among other competitive priorities, including cost, delivery, and quality (Pérez-Pérez et al., 2019). Overcoming the traditional trade-offs between a key aspect of a manufacturer's flexibility—that is, product customization—and cost, delivery, and quality is an ambidextrous organizational capability known as mass customization capability (MCC) (Trentin et al., 2020; Zhang et al., 2024). This capability is gaining increasing attention from companies, as product customization is becoming the new norm in the manufacturing sector (Genedge; PwC & Oracle Alliance, 2024). In this context, MCC can foster innovation (Qi et al., 2020), improve several dimensions of firm performance, including environmental sustainability (Sheng et al., 2021), and become a source of competitive advantage (Jain et al., 2022). The growing importance of MCC in practice has spurred a considerable body of research aimed at understanding how to develop this capability (see Suzić et al., 2018 for a recent review on the topic). Prior research has also observed that improving MCC is a complex endeavor that requires putting multiple enablers in place, and that uneven or interrupted paths toward this goal are not unusual (Suzić et al., 2018). To develop guidelines capable of supporting companies in this challenging process, it is crucial to understand the relationships among MCC enablers, as firms implementing mass customization must decide not only what enablers should be put in place but also the order in which they should be implemented (Suzić et al., 2018).

However, most prior research on the enablers of MCC has focused on their independent effects on this capability (Sheng et al., 2023). The relationships among MCC enablers and their combined effects on MCC require additional research (Jain et al., 2023; Sheng et al., 2023). In particular, the precedence relationships and the resulting sequential path toward MCC that characterize most of the mass customization implementation guidelines available in the literature should be reconsidered (Suzic & Forza, 2023). A strong challenge to this sequential path is presented by resource orchestration theory (ROT), since ROT posits that organizational capabilities, such as MCC, stem from bundling (i.e., jointly deploying) multiple interdependent and mutually reinforcing resources (Hitt et al., 2016; Liu et al., 2016; Sirmon et al., 2007), defined as tangible and intangible assets that a firm controls (Sirmon et al., 2008), including organizational practices. However, this theoretical lens has not been applied to the investigation of MCC antecedents (see Liu et al., 2023) and, particularly, the investigation of their combined effects on MCC.

The present paper aims to narrow this gap by drawing on ROT arguments to explain the effect on MCC of bundling three organizational practices that directly correspond to the fundamental enablers of mass customization identified by prior influential research and whose joint effect on MCC has remained unexplored (see "Appendix 1"), namely knowledge absorption from customers (KAfC), product modularity (PM), and online sales configurator use (OSCU). By integrating ROT arguments with the fit-as-covariation perspective and prior MCC research, the present study conceptually develops the hypothesis that the fit-as-covariation (i.e., the bundling) of KAfC, PM, and OSCU has a stronger positive association with MCC than the same practices implemented in isolation. The present study tested this hypothesis using covariance-based structural equation modeling (CB-SEM) and survey data from 213 manufacturing plants in three industries across 16 countries in Asia, America, and Europe. By doing so, this study improves the understanding of how to develop MCC, which can help companies not only improve their profitability but also foster innovation and transition toward sustainable production.

The remainder of this paper is organized as follows. The next section reviews the relevant literature and conceptually develops the research hypothesis. The following sections describe the data and the measures used to test the hypothesis, show the quality of the measures, present the results of the main analysis, and introduce the supplementary analyses, whose details are reported in the online supplement to this paper. The theoretical and managerial implications of the findings, as well as the study's limitations and opportunities for future research, are then discussed. Finally, some concluding remarks are provided concerning the main message of the paper.

Literature Review and Research Hypothesis

This section begins with a review of the literature linking mass customization with flexibility. It then explains why the three organizational practices of interest here map one-to-one onto the fundamental building blocks of mass customization identified by Salvador et al.'s (2009) influential work. Finally, it presents the conceptual arguments that led to the research hypothesis.

Mass Customization and the Role of Flexibility in its Context

Mass customization seeks to combine the best of custom manufacturing, in terms of individualized products, with the best of mass production, in terms of cost, delivery, and quality performance (Squire et al., 2006). Prior research has distinguished different mass customization strategies that reflect different customer utility functions (Trentin & Salvador, 2023). For example, when customers value a high degree of product customization more than they value delivery speed, the mass customization strategy should involve customers at the design or fabrication stage of the value chain (Trentin & Salvador, 2023). On the other hand, when customers are not willing to sacrifice delivery speed, "they must be involved at a later stage and customization takes place within the constraints of pre-engineered product options or variants" (Trentin & Salvador, 2023, p. 24). In the former case, prior research has used the term "full mass customization," while in the latter case, it has spoken of partial mass customization (e.g., Huang et al., 2010; Sandrin et al., 2018).

The notion of mass customization (capability) has long been related to the concept of flexibility in two different ways. One perspective sees flexibility as an enabler of MCC. This view dates back to Pine's (1993) seminal work on mass customization. Unsurprisingly, the earliest literature review on mass customization, conducted by da Silveira et al. (2001), defined mass customization in a way that emphasized the role played by flexible processes in the development of this capability. Similarly, process flexibility was identified by Zipkin (2001) as one of the fundamental enablers of MCC. Two years later, Fogliatto et al. (2003) considered not only process flexibility but also "the flexibility of design and/or supply delivery" (pp. 1811–1812) in their flexibility-driven index, which aimed to assess the feasibility of mass customization. Elements of flexibility beyond the traditional boundaries of the firm were also identified in studies by Brabazon et al. (2010), Salvador et al. (2015), Trentin et al. (2015), and Ullah and Narain (2022). Besides reiterating the message on the importance of flexibility at the plant level, Brabazon et al. (2010) showed the role that interdealer trading flexibility—a form of routing flexibility involving the downstream supply chain—plays in the pursuit of MCC in the automotive industry. Regarding the upstream supply chain, Trentin et al.'s (2015) longitudinal case study indicated supplier flexibilization as one of the factors that had improved MCC at the case company. In the same year, Salvador et al. (2015) reported large-scale empirical evidence of the MCC-enabling role of flexible manufacturing resources, defined in that study as including flexible suppliers. Seven years later, these findings were corroborated and extended by Ullah and Narain's (2022) survey-based study, which found empirical support for the positive effect on MCC of not only supplier flexibility but also sourcing flexibility. At a higher level of abstraction, Kortmann et al. (2014) examined and reported large-scale empirical evidence for the MCC-enabling role of strategic flexibility, which depends not only on the flexibility of a firm's resources but also on the firm's ability to reconfigure them. Unsurprisingly, flexible manufacturing systems and reconfigurable manufacturing systems have often been mentioned as important enablers of mass customization (Gao et al., 2021; He & Smith, 2024; Jain et al., 2023).

Other authors, however, have seen flexibility not as an enabler of MCC but as one of the two poles of the tension whose reconciliation is the very essence of MCC. For example, Birkinshaw and Gupta (2013) observed that mass customization makes it possible to reconcile efficiency and flexibility in the manufacturing sector. In the same vein, subsequent research has observed that mass customization is expected to overcome the traditional trade-off between flexibility and other dimensions of operational performance (Trentin et al., 2020; Wiengarten et al., 2017). Similarly, recent research in the construction industry has viewed mass customization as the key to simultaneously increasing flexibility and efficiency (Cao et al., 2021; Formoso et al., 2022). Notably, this view implicitly equates flexibility with the ability to provide customized products, that is, with product flexibility as defined by Vickery et al. (1999). On the other hand, the view of flexibility as an enabler of MCC focuses on other dimensions of flexibility, such as process flexibility or supplier flexibility, as explained above.

Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks

Knowledge absorption from customers is the practice of acquiring, assimilating, and exploiting knowledge gained from customers (e.g., Yang & Yee, 2022; Zhang et al., 2015b). This practice maps onto the first of the three fundamental building blocks of mass customization identified by Salvador et al. (2009)—solution space development. This building block points to the necessity for a mass

customizer to define its solution space, that is, the "predefined space of possible outputs" (Salvador et al., 2020, p. 4), based on a clear understanding of customers' idiosyncratic needs and, specifically, of the product attributes along which customers' idiosyncratic needs diverge the most (Salvador et al., 2009). As such, solution space development clearly implies the acquisition, assimilation, and exploitation of customer knowledge.

Knowledge absorption from customers adds to a company's flexibility by enabling the organization to keep its solution space aligned with its customers' evolving needs (Zhang et al., 2015b). For example, customers' post-purchase feedback on the value received from existing solutions can be gathered, analyzed, and incorporated into improved solutions. Keeping the solution space aligned with changes in customers' needs is a prerequisite to fulfilling customer orders using predefined solutions and not having to resort to engineered-to-order ones. In turn, this is essential to infusing "flexibility into the product architectures as well as into the sales and transformation processes" without compromising other dimensions of operational performance (Salvador et al., 2020, p. 4).

Product modularity is the practice of designing products composed of parts that can be physically separated and recombined to create a variety of product configurations (Mikkola, 2007; Salvador, 2007; Wurzer & Reiner, 2018). This practice maps onto the second of the three fundamental building blocks of mass customization identified by Salvador et al. (2009)—robust process design. This building block points to the requirement that a mass customizer fulfill differentiated customer needs by reusing or recombining existing organizational and value-chain resources (Salvador et al., 2009). Product modularity enables a company to achieve this by creating product variety in a combinatorial fashion from a relatively small number of components (Ulrich, 1995). Consequently, product components can be made in volume using mass-production techniques, which allow manufacturers to achieve the low cost and consistent quality typical of repetitive manufacturing (Duray et al., 2000).

Product modularity is a key enabler of strategy flexibility (Worren et al., 2002). In particular, PM helps a manufacturer keep its solution space aligned with changes in customers' functional requirements, as the number of product components affected by these changes is minimal (Gauss et al., 2022; Ulrich, 1995). In addition, PM allows the postponement of the creation of product variety along the manufacturing and distribution process (Verma & Chatterjee, 2023), thus improving several dimensions of operational performance (see Trentin & Salvador, 2023).

Finally, OSCU is the practice of enabling customers to self-customize their product solutions online within the constraints specified by the manufacturer (Sandrin et al., 2017; Tseng & Piller, 2003). This practice maps onto the last of the three fundamental building blocks of mass customization identified by Salvador et al. (2009)—choice navigation. This building block points to the necessity for a mass customizer to help its customers identify their own solutions within the manufacturer's solution space "while minimizing complexity and the burden of choice" (Salvador et al., 2009, p. 74). An online sales configurator enables a company to do this by giving customers the freedom to explore the company's solution space and make their choices within the constraints specified by the company, ideally in a flexible and focused manner (Trentin et al., 2013).

The use of an online sales configurator reconciles product flexibility with cost, delivery, and quality in at least two ways. First, it eliminates sales configuration errors, which require time-consuming and costly interactions between the customer and the manufacturer to fix, or if these errors remain undetected, may impair product quality (Heiskala et al., 2007). Second, OSCU increases the number of customer orders that are fulfilled using predefined solutions instead of engineered-to-order ones (Heiskala et al., 2007). Both mechanisms contribute to improving cost, delivery, and quality performance when customized products are provided (see Zhang, 2014 for a review of the research on the impacts of configurators on firm performance).

The practices outlined above can support a wide range of mass customization strategies that are characterized by different degrees of product customization (e.g., Duray et al., 2000; Forza & Salvador, 2006). However, as the degree of product customization approaches its maximum, the implementation of OSCU becomes increasingly difficult (Forza & Salvador, 2006).

Hypothesis Development

A useful theoretical framework for this study is ROT. According to ROT, organizational capabilities stem from bundles of multiple, interdependent, and mutually reinforcing resources (Hitt et al., 2016; Liu et al., 2016; Sirmon et al., 2007). It is the "fit or alignment" of these resources "rather than the independent effects of the individual resources" (Liu et al., 2016, p. 14) that leads to organizational capabilities and, ultimately, to the creation of value for customers and owners (Sirmon et al., 2007). This notion of alignment among multiple interdependent and mutually reinforcing resources is captured well by the fit-as-covariation perspective identified by Venkatraman (1989). This perspective, not unlike the perspectives termed "fit-as-gestalts" and "fit-as-profile deviation" in the same paper, conceptualizes fit as internal consistency among three or more variables (Venkatraman, 1989). The fit-as-covariation

perspective, however, is more precise than the other two in specifying the functional form that internal consistency should take: "In this case, internal consistency requires that a higher value of any one of the considered variables is associated with higher values of all the other variables" (Sandrin et al., 2018, p. 338). Another reason why this perspective on fit aligns well with ROT's notion of resource bundling is that the outcome of the multilateral interactions among the three or more variables that comprise the bundle is captured well by the performance effect of fit-as-covariation (Tanriverdi & Venkatraman, 2005).

In summary, ROT arguments and Venkatraman's (1989) work on the conceptualization of fit imply that organizational capabilities stem from the fit-as-covariation of multiple, interdependent, and mutually reinforcing resources rather than from the independent effects of the same resources considered in isolation. This major premise can be combined with another premise, which rests on the direct correspondence of KAfC, PM, and OSCU with the fundamental building blocks of mass customization identified by Salvador et al.'s (2009) influential work. This correspondence implies that KAfC, PM, and OSCU are key resources for MCC. From these two premises, it follows that the fit-as-covariation of these three specific resources explains and predicts the organizational capability of mass customization better than the independent effects of the same resources considered in isolation.

The result of this deductive reasoning is corroborated by a set of intertwined arguments that, for the sake of conciseness, are reported in Appendices 2 and 3, where they are also illustrated by company case examples based on the MCC literature or the authors' experience with manufacturers pursuing MCC. Appendix 2 provides a comprehensive and systematic explanation of the mechanisms whereby KAfC, PM, and OSCU mutually facilitate their implementation in the pursuit of MCC (i.e., why PM facilitates both OSCU and KAfC, why OSCU facilitates both KAfC and PM, and why KAfC facilitates both PM and OSCU). These mechanisms of mutual facilitation contribute to explaining why MCC is better predicted by the joint presence of these three practices than by the same practices considered in isolation. Likewise, Appendix 3 provides a comprehensive and systematic explanation of the mechanisms whereby the three practices mutually reinforce their benefits in terms of MCC (i.e., why OSCU reinforces the positive effect on MCC of both KAfC and PM, why PM reinforces the positive effect on MCC of both OSCU and KAfC, and how KAfC reinforces the positive effect on MCC of both PM and OSCU). Since a manufacturer that understands these synergies is likely to implement these practices together (see Aral et al., 2012, for the same logical point, although applied to a different research aim), these complementarity mechanisms contribute to explaining why MCC is better predicted by the joint presence of these practices than by their isolated effects.

Besides corroborating the line of reasoning that combines ROT arguments, Venkatraman's (1989) notion of fit-as-covariation, and Salvador et al.'s (2009) influential work, Appendices 2 and 3 also overcome the concern that simply advocating the bundling of KAfC, PM, and OSCU based on this line of reasoning might be considered by managers as overly generic or lacking in substance. Based on the above, the following research hypothesis is posited:

Hypothesis: The fit-as-covariation of KAfC, PM, and OSCU has a stronger positive association with a manufacturer's MCC than KAfC, PM, and OSCU implemented in isolation.

The effect of the fit-as-covariation of the three practices on MCC is captured by the covariation model depicted in Fig. 1a, while the effects of the same practices implemented in isolation are captured by the independent-effects model depicted in Fig. 1b. The research hypothesis involves a comparison of the two models.

Method

This study follows the approach recommended for confirmatory survey research, which is the type of survey research that aims to test theory-driven hypotheses (Forza & Sandrin, 2023). Accordingly, this section begins with a description of the data collection procedures and continues with a description of the measures used to test the hypothesis and the results of the analyses performed to assess measurement quality. Finally, this section describes the testing procedure, which is based on Venkatraman's (1989) influential work on alternative notions of fit and the associated testing procedures, as well on subsequent studies by the same author (Tanriverdi & Venkatraman, 2005; Venkatraman, 1990).

Data Collection

The data for hypothesis testing were sourced from the fourth and most recent edition of the High-Performance Manufacturing (HPM) research initiative. This is an international survey that has targeted, since its first edition, medium-to-large manufacturing plants operating within three industries: electronics, machinery, and transportation equipment. The number of countries involved has progressively increased from one edition to the next and now includes 16 countries across America, Asia, and Europe. In exchange for its participation, each plant received a comprehensive benchmarking report that allowed it to compare

Fig. 1 Conceptual models to be compared

its levels of performance and practice adoption against the values of descriptive statistical indicators, such as averages, maxima, and minima, derived from the subsample of plants in the same industrial sector worldwide. This incentive contributed to a response rate of around 65% per country. Twelve distinct questionnaires, each covering specific topics, were provided to each plant. Two plant respondents for each questionnaire were selected based on their expertise in the relevant subject matter, except for the questionnaire on accounting, which was submitted to one respondent.[1] The sample we used to test the hypothesis is described in Table 1.

The fourth round of the HPM survey was specifically designed to collect data on a set of manufacturing and supply chain management practices that includes the three practices of interest in the present study. In addition, the HPM survey focuses on mid- to large-sized manufacturing plants, whose relatively greater resources make it more likely that the application of the surveyed practices can be observed (Morita et al., 2018). Undeniably, practices such as PM or OSCU may be more relevant in some industries than in others. However, their adoption in the machinery, transportation equipment, and electronics industries has been discussed in business sources as well as in academic papers (e.g., Bannasch et al., 2014; Blazek et al., 2021; Mahlamäki et al., 2020). Consequently, our sample is appropriate for the purposes of the present study.

Measures and Their Quality

The measurement scales for the focal constructs are presented in Table 2. For MCC, we used Zhang et al.'s (2020) validated four-item scale adapted from Tu et al. (2001). For KAfC and PM, we employed, respectively, Phan et al.'s (2020) validated five-item scale and Liu et al.'s (2010) validated three-item scale. For all these scales, the

[1] More details on the data collection process can be found in Ortega-Jimenez et al. (2020).

Table 1 Sample distribution by industry and country

Industry	Frequency	%
Electronics	70	32.9
Machinery	86	40.4
Transportation equipment	57	26.8
Total	213	100.0
Country	**Frequency**	**%**
Brazil	9	4.2
China	19	8.9
Finland	12	5.6
Germany	19	8.9
Israel	6	2.8
Italy	25	11.7
Japan	18	8.5
South Korea	21	9.9
Spain	16	7.5
Sweden	3	1.4
Switzerland/Austria	9	4.2
Taiwan	23	10.8
UK	13	6.1
USA	7	3.3
Vietnam	13	6.1
Total	213	100.0

participants responded to each item on a five-point Likert-type scale, where 1 = strongly disagree and 5 = strongly agree. Finally, for OSCU, we used a single-item measure, based on Bergkvist and Rossiter's (2007) argument that single-item measures are sufficient when a) "the object of the construct [in our case, the online sales configurator] is 'concrete singular,' meaning that it consists of one object that is easily and uniformly imagined [by the survey respondents]" and b) "the attribute of the construct [in our case, the extent to which the online sales configurator is used] is 'concrete,' again meaning that it is easily and uniformly imagined" (Bergkvist & Rossiter, 2007, p. 176). The instructions for the OSCU item read: "For which of the following marketing and sales activities does your plant use the Internet or EDI [that is, electronic data interchange]? (1 = not at all, …, 5 = completely)."

Since the focal constructs are plant-level characteristics that were measured using individual-level data collected from multiple respondents per plant, agreement among informants is essential: "To the extent that responses across multiple informants evaluating the same system […] are consistent, the researcher infers this is due to a common system-level trait driving the informant reports" (Ketokivi, 2019, pp. 383–384). To assess inter-rater agreement, we used the ratio method developed by James et al. (1984). All inter-rater agreement coefficients (IRACs) were well above 0.8 (Table 2), indicating good agreement among the informants (Boyer & Verma, 2000). Consequently, the informants' scores were averaged to arrive at a plant-level score for each focal construct.

Since the measures of the focal constructs are perceptual, we assessed their psychometric properties through confirmatory factor analysis (CFA) performed using IBM's SPSS Amos version 22 software. To evaluate unidimensionality and convergent validity, a model was specified in which each item was constrained to load solely on its intended construct while allowing the four latent constructs to correlate freely. The model showed a good fit with the data, as evidenced by standard fit indices: χ^2 (df) = 142.98 (60), $\chi^2/df = 2.38$; comparative fit index (CFI) = 0.92, incremental fit index (IFI) = 0.92, Tucker–Lewis index (TLI) = 0.90, root-mean-square error of approximation (RMSEA) (90% confidence interval) = 0.081 (0.064–0.098). Additionally, standardized factor loadings for all items exceeded 0.50 and were significant at $p < 0.01$. Finally, all average variance extracted (AVE) scores exceeded 0.50. Together, these results suggest unidimensionality and good convergent validity. All composite reliability (CR) values were above 0.70, which indicates satisfactory reliability. Finally, the application of Fornell and Larcker's (1981) procedure suggests good discriminant validity (Table 3).

Finally, we assessed common method bias, which could be a concern when using perceptual measures. However, it is worth emphasizing that, in our case, this concern is mitigated by the fact that the focal constructs were measured using different informants so that no informant was shared by any pair of constructs (see Podsakoff et al., 2003). Nonetheless, we conducted Harman's single-factor test using both exploratory and confirmatory factor analysis (see Podsakoff et al., 2003). The results of these analyses do not suggest that method bias is a concern in this study.

Testing Procedure

To test the hypothesis, we compared the effect on MCC of a reflective, second-order latent factor representing the fit-as-covariation of KAfC, PM, and OSCU with the independent effects of the same three variables on the same capability. In the former model, the second-order factor accounts for the complementarity and covariance among the considered practices in the pursuit of MCC (see Tanriverdi & Venkatraman, 2005, although in a different context). On the contrary, the latter model does not posit any incremental explanatory power for the complementarity and covariance of these practices (see Tanriverdi & Venkatraman, 2005, although in a different context).

Table 2 Measurement scales

Construct Composite reliability, Average variance extracted, Inter-rater agreement coefficient	Measurement item (item code)	Standardized factor loading[a]
Knowledge absorption from customers[i] (Phan et al., 2020, p. 395)		
CR = 0.88	"We obtain a great amount of our product knowledge from our customers." (KAfC1)	0.76
AVE = 0.59		
IRAC = 0.91	"Our customers provide us with valuable information on product innovation." (KAfC2)	0.74
	"We have learned a lot from our customers as part of our product development process." (KAfC3)	0.85
	"We quickly adopt new technologies by applying what we learn from our customers." (KAfC4)	0.78
	"We systematically check whether we have applied the knowledge we acquire from our customers regarding our products." (KAfC5)	0.70
Product modularity[ii] (Liu et al., 2010, p. 1010)		
CR = 0.76	"Our products are modularly designed, so they can be rapidly built by assembling modules." (PM1)	0.85
AVE = 0.52		
IRAC = 0.84	"We have defined product platforms as a basis for future product variety and options." (PM2)	0.52
	"Our products are designed to use many common modules." (PM3)	0.77
Online sales configurator use[iii] *(see* Roth et al., 2008, p. 33)		
CR = 1	"Providing online customized customer service, where customers can configure the product within the constraints stated by the plant." (OSCU1)	1
AVE = 1		
IRAC = 0.83		
Mass customization capability[iv] (Zhang et al., 2020, p. 492)		
CR = 0.81	"We are highly capable of large-scale product customization." (MCC1)	0.72
AVE = 0.52		
IRAC = 0.86	"We can easily add significant product variety without increasing cost." (MCC2)	0.64
	"We can customize products while maintaining high volume." (MCC3)	0.79
	"Our capability for responding quickly to customization requirements is very high." (MCC4)	0.73

[a]All estimated factor loadings are statistically significant with $p < 0.01$

[i]Downstream supply chain management questionnaire

[ii]New product development questionnaire

[iii]Information system management questionnaire

[iv]Process engineering questionnaire

In line with several previous studies on the determinants of MCC (e.g., Liu et al., 2006; Zhang et al., 2014), we controlled for the effects of the country and industry in which a manufacturer operates and the size of the manufacturing company, measured with the natural logarithm of the number of personnel employed (e.g., Huang et al., 2008). Unlike plant size and the two industry dummies, the numerous country dummies could not be included in the two models due to our sample size. Thus, to rule out the potential effects of country, we followed the approach of Liu et al. (2006) and Sandrin et al. (2018) by employing in all analyses the standardized residuals from the linear ordinary least square regression analysis of each MCC item on the country dummies.

Results

Using IBM's SPSS Amos version 22 software, we estimated and compared the two models through CB-SEM and applied the criteria suggested by Venkatraman (1989) and/or Venkatraman (1990). The first criterion involves

Table 3 Discriminant validity of MCC, KAfC, PM, and OSCU

Construct	AVE square root	Correlations			
		MCC	KAfC	PM	OSCU
MCC	0.72	1.00			
KAfC	0.77	0.22	1.00		
PM	0.72	0.26	0.14	1.00	
OSCU	1.00	0.15	0.09	0.13	1.00

evaluating the models' goodness-of-fit statistics. Both models exhibit similar and satisfactory fit indices. For the covariation model, χ^2 (df) = 162.53 (95), χ^2/df = 1.71; CFI = 0.94, IFI = 0.94, TLI = 0.92, RMSEA (90% confidence interval) = 0.058 (0.042–0.073). For the independent-effects model, χ^2 (df) = 158.00 (87), χ^2/df = 1.82; CFI = 0.93, IFI = 0.94, TLI = 0.91, RMSEA (90% confidence interval) = 0.062 (0.046–0.077). However, the covariation model is preferred due to its greater parsimony (Venkatraman, 1990).

The second criterion is the target coefficient—that is, the ratio of the χ^2 value of the independent-effects model over the χ^2 value of the covariation model—whose maximum value is 1. Here, the target coefficient is 0.97, which is close to 1. This indicates that the covariation model, which is more parsimonious, explains the relationships among the first-order factors almost as well as the independent-effects model.

The third criterion considers the statistical significance of the loadings of the first-order factors on the second-order factor, while the fourth criterion evaluates the statistical significance of the structural path linking the second-order factor to the outcome variable, that is, to MCC. As illustrated in Fig. 2, all the loadings of the first-order factors on the second-order factor are positive and highly significant, and the second-order factor has a highly significant positive impact on MCC.

The last criterion compares the squared multiple correlation of MCC in the two models, which is the equivalent of R^2 in the regression analysis. The value of the MCC squared multiple correlation in the covariation model (41.9%) is much greater than the same value in the independent-effects model (13.9%).

Collectively, these results corroborate our hypothesis by favoring the covariation model (Fig. 2) over the independent-effects model (Fig. 3). Specifically, criteria 1, 2, and 3 support the existence of the fit-as-covariation of KAfC, PM, and OSCU in the pursuit of MCC. Criterion 4 shows that the fit-as-covariation of these three practices has a highly significant positive association with MCC. Finally, criterion 5 shows that the fit-as-covariation of these practices explains much more of the MCC variation in our sample than do the independent effects of the same practices considered in isolation. Notably, in the independent-effects model, the positive effects of KAfC and PM on MCC are highly significant, but the positive effect of OSCU on MCC is not significant, even with a generous 0.10 p value. This result provides further corroboration of our conceptual argument that MCC is better explained and predicted by a model in which the three practices are bundled.

Finally, we performed a range of supplementary analyses to assuage possible concerns about the measures used for OSCU and MCC. These analyses, which are presented in detail in the online supplement to this paper, supported our hypothesis, thus showing the robustness of our findings.

Discussion

This section begins with a discussion of the implications of our findings for theory and practice. Subsequently, it explains the limitations of our work and discusses the corresponding opportunities for future research.

Theoretical Implications

Our findings have theoretical implications for three different but related streams of research: flexibility, MCC, and resource orchestration. The first contribution lies in our positioning of MCC research, including the results of the present study, in the context of flexibility research. Our systematic review of the literature linking flexibility and mass customization shows that flexibility plays a key role in both the conceptualization of MCC and the implementation of this capability. On the one hand, flexibility is one of the poles of the tension that the ambidextrous organizational capability of mass customization is expected to reconcile (e.g., Wiengarten et al., 2017). On the other hand, flexibility is one of the enablers of this capability (e.g., Fogliatto et al., 2003). Interestingly, these two roles have coexisted in the literature, with some recent works focusing on new solutions to increase manufacturing flexibility to improve MCC (e.g., Hashemi-Petroodi et al., 2022; Vještica et al., 2023), while other recent studies have viewed mass customization as the key to simultaneously increasing flexibility and efficiency (Cao et al., 2021; Formoso et al., 2022). This dual role played by flexibility in the context of MCC implies that MCC research is inherently relevant to flexibility research.

Notably, these two roles do not constitute a contradiction but are fully consistent with the results of prior

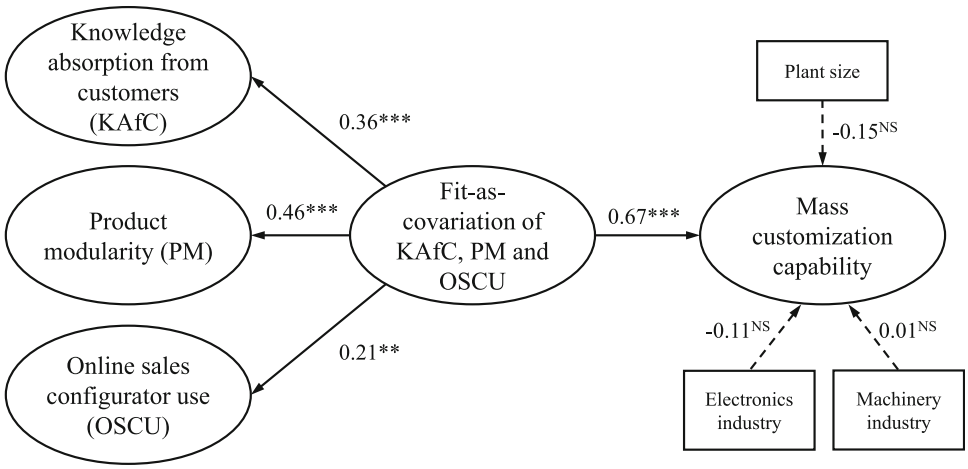

Fig. 2 Covariation model: structural model estimates (***$p < 0.01$; **$p < 0.05$; $^{NS}p > 0.10$)

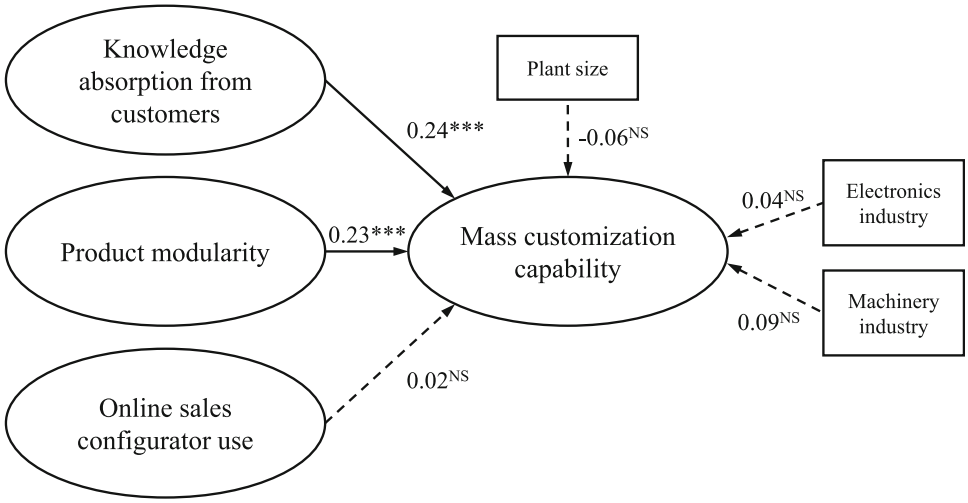

Fig. 3 Independent-effects model: structural model estimates (***$p < 0.01$; **$p < 0.05$; $^{NS}p > 0.10$)

research on flexibility types or dimensions.[2] How different types of flexibility relate to each other is one of the issues addressed by the stream of research on the conceptualization and operationalization of manufacturing and supply chain flexibility (Pérez-Pérez et al., 2019). Our systematic literature review shows that when flexibility is involved in the conceptualization of MCC, it is understood as product flexibility; on the other hand, when it is mentioned as an enabler of MCC, it is understood as the flexibility of the manufacturing process or of the upstream or downstream supply chain, with a focus that—reflecting the main research trajectory identified by Varma et al. (2024) in the domain of flexibility—has progressively broadened from in-house flexibility to include inbound and outbound flexibilities (see Dey et al., 2019 for this categorization of flexibility types). Notably, one of the accepted relationships between the various dimensions of flexibility is the positive association between process flexibility and product flexibility (Jain et al., 2013; Parker & Wirth, 1999). This accepted relationship is entirely consistent with the two roles that flexibility plays in the implementation and conceptualization of MCC; that is, flexibility (referring to process flexibility) enables MCC, which is defined as the ability to reconcile flexibility (referring to product flexibility) with low cost, fast delivery, and high quality. This dual role can also be interpreted through the lens of the input-throughput-output model recently used by Höse et al. (2023) to classify the different types of flexibility, which states that product-related (or output) flexibility stems from process-related (or throughput) and resource-related (or input) flexibilities.

Interestingly, the results of the present study can also be discussed in relation to Pérez-Pérez et al.'s (2019) integrative framework on the antecedents, building blocks, and consequences of manufacturing and supply chain flexibility. Two of these building blocks can be related to the organizational practices of interest here: KAfC and OSCU map onto the "information sharing and communication" building block, while PM maps onto the "processes"

[2] We use the terms "flexibility type" and "flexibility dimension" as synonyms, in accordance with the vast majority of the flexibility literature (e.g., Pérez Pérez et al., 2016).

building block (Pérez-Pérez et al., 2019, p. 12). Therefore, our results regarding the added value of bundling KAfC, OSCU, and PM can be seen as echoing Pérez-Pérez et al.'s (2019) observation that the building blocks of flexibility are "interconnected and reinforcing approaches" (p. 12). In addition, Pérez-Pérez et al. (2019) observe that organizational capabilities, such as agility, are among the outcomes of the interdependent and mutually reinforcing building blocks of flexibility. This observation is echoed by our findings, since we showed that bundling KAfC, OSCU, and PM—three practices that map onto two of the flexibility building blocks identified by Pérez-Pérez et al. (2019)—is positively associated with the organizational capability of mass customization.

The second contribution of the present study concerns the relationships between MCC enablers and how these relationships affect MCC. Even though prior research has investigated the effect of one or another of our focal practices—considered in isolation—on MCC (e.g., Zhang et al., 2015b, 2019), our conceptual and empirical results are the first concerning their joint effect on MCC. Given the lack of prior studies on this issue, we can only compare our findings with prior research that explicitly or implicitly suggests relationships between MCC enablers whose definitions conceptually overlap—to various extents—with two or more of the practices of interest here (see Appendix 1).

On the one hand, our results are consistent with the message that PM and OSCU are positively associated with one another, which can be inferred from Peng et al. (2011) and Zhang et al. (2015a). Likewise, our results are in line with the positive association that was found by Tu et al. (2004) between PM and KAfC. Finally, our results are consistent with the pairwise complementarities found by Salvador et al. (2015) among three different "resource types" (Salvador et al., 2015, p. 618): customer involvement, which overlaps with KAfC; the endowment of flexible manufacturing resources, which embraces five different resources, including PM; and product management tools, which encompass three distinct resources, including OSCU.

On the other hand, our results challenge the mainly sequential logic that dominates the literature reviewed by Suzić et al. (2018), that is, the literature that contains guidelines for the implementation of mass customization. Their review found an overall agreement that PM—as part of product platform development—should precede information technology–based product configuration, which includes OSCU. This relationship, in which PM precedes OSCU, might also be inferred from Purohit et al.'s (2016) findings. However, our results showed that the joint effect of PM, OSCU, and KAfC explains substantially more MCC variation (41.9%) than the effects of the same practices when considered independently (13.9%). The amount of MCC variation explained by our covariation model indicates a large effect size according to Cohen et al. (2003). In addition, this effect size is greater than that reported in most previous survey-based studies on the antecedents of MCC. Of 22 studies that tested models with MCC as a dependent variable, only three (i.e., Migdadi, 2022; Ullah & Narain, 2021; Wang et al., 2015; all of which use partial least squares structural equation modeling) explain more MCC variation than our covariation model. Conversely, the two highest amounts of MCC variation explained by the studies that used regression analysis or CB-SEM are smaller than the amount explained by our covariation model: 36% in Salvador et al. (2015) and 29% in Huang et al. (2010). Collectively, our conceptual and empirical findings suggest that with a strictly sequential implementation process, the adoption of the first practice in the sequence (e.g., OSCU) could possibly fail due to lack of support from the two other practices; in addition, supposing this were not the case, the synergies among the three practices would be fully captured only at the end of the process, when all the practices have been implemented. This means that a strictly sequential implementation, even if it did not lead to an interrupted path, would certainly delay the full realization of the benefits of KAfC, PM, and OSCU in the pursuit of MCC.

By either echoing or challenging prior mass customization research results, our findings add to the discussion on the relationships among MCC enablers and how these relationships affect MCC. Although crucial to the development of mass customization implementation guidelines (Suzic & Forza, 2023; Suzić et al., 2018), this issue has attracted relatively little research, especially on the interplay among larger sets of enablers (Jain et al., 2023). By advancing knowledge of this issue, our study complements Salvador et al.'s (2009) influential work, which identified three fundamental building blocks of mass customization but left it up to managers to decide whether to implement them simultaneously or in a particular sequence. Since KAfC, PM, and OSCU map one-to-one onto those building blocks, our results argue in favor of the simultaneous, rather than sequential, implementation of the fundamental building blocks of mass customization identified by Salvador et al. (2009).

A final contribution of the present paper to the MCC literature lies in our borrowing of ROT arguments to generate novel insights into the process of developing MCC. The existing literature has adopted various theoretical lenses to investigate the antecedents of MCC, including the theory of sociotechnical systems and the resource-based view (see Liu et al., 2023). However, to the best of

our knowledge, prior research on the antecedents of MCC has not yet exploited ROT,[3] whose aim is to elucidate the process through which executives manage firm resources to create and maintain value for customers and owners (Sirmon et al., 2007, 2011). A key step in this process consists of bundling multiple interdependent and mutually reinforcing resources to develop organizational capabilities (Chirico et al., 2025; Hitt et al., 2016; Liu et al., 2016). By drawing upon this central tenet of ROT, the present paper also makes an incremental contribution to the stream of research on resource orchestration.

Prior research in this stream has conceptualized the notion of resource bundling using the fit-as-profile deviation perspective (e.g. Liu et al., 2016) or the fit-as-moderation perspective (e.g. Deligianni et al., 2019). To the best of our knowledge, the present study is the first to establish a logical connection between ROT's notion of resource bundling and the fit-as-covariation perspective. In a context in which ROT is attracting considerable attention from researchers beyond the confines of strategy research (e.g., Chirico et al., 2025; Jiang et al., 2024), this connection may help future research take full advantage of Venkatraman's (1989) work on alternative notions of fit and on the associated testing procedures. When the bundling of three or more resources mutually reinforces their effects on a given criterion variable and mutually facilitates their creation, the other five perspectives identified by Venkatraman (1989) appear less appropriate for conceptualizing the resource bundle. First, the fit-as-matching perspective cannot capture the fit between more than two variables (Venkatraman, 1989). Second, the fit-as-gestalts perspective and the fit-as-profile deviation perspective view fit as internal consistency between three or more variables but do not require that the pattern of internal consistency be a pattern of covariation (see Venkatraman, 1989). Finally, the fit-as-moderation perspective and the fit-as-mediation perspective capture only part of the complex set of intertwined relationships that explain the existence of such a resource bundle: The fit-as-mediation perspective does not capture the fact that the bundled resources mutually reinforce their effects on a given criterion variable, while the fit-as-moderation perspective does not capture the fact that the bundled resources mutually facilitate their creation, thus affecting the same criterion variable not only directly but also indirectly through the other resources of the bundle (see Venkatraman, 1989).

Finally, the present study provides empirical corroboration for one of the central tenets of ROT—that is, that organizational capabilities stem from bundles of multiple, interdependent, and mutually reinforcing resources (Hitt et al., 2016; Liu et al., 2016; Sirmon et al., 2007). By focusing on a specific bundle that prior research has not examined, our conceptual results apply this highly abstract tenet of ROT to the organizational capability of mass customization, and our empirical results corroborate this tenet in the specific context of MCC. Overall, this middle-range theorizing effort (see Bourgeois, 1979) adds to the resource orchestration literature, as the latter has rarely identified the specific bundles needed to develop specific capabilities (Hughes et al., 2018).

Managerial Implications

From a practical standpoint, this study can help companies create flexible systems that are able to provide customized products without compromising cost, delivery, or quality. It does so in two ways. First, it makes managers aware that they should strive to simultaneously increase PM, KAfC, and OSCU to reconcile product flexibility with low cost, fast delivery, and high quality. Our conceptual arguments, corroborated by our empirical findings, imply that any partial approach in which only a subset of these practices is implemented will make their implementation more difficult and hinder the full realization of their potential benefits in the pursuit of MCC. In particular, our data show that adopting an online sales configurator without adequately investing in the ability to absorb customer knowledge and modularize the product architecture does not have a statistically significant positive effect on MCC. This finding points once more to the risk of adopting technological solutions for mass customization without what, three decades ago, Hart (1995) termed "organizational readiness" (p. 44). Likewise, any approach in which OSCU, KAfC, and PM are implemented sequentially will certainly delay the achievement of the same benefits and might possibly lead to failure in the implementation of the early practices in the sequence and, therefore, to an interrupted path. Of course, resource constraints could prevent a simultaneous, steep increase in the level of all these practices. In this case, a feasible approach to avoid the disadvantages of working on only one practice at a time might be to make simultaneous but gradual improvements, for example, by focusing on one product family at a time.

Second, this paper helps managers build support for the possibly gradual but simultaneous increase of KAfC, PM, and OSCU. This coordinated move requires information exchange and collaboration across multiple functional departments within a manufacturing organization (at the very least, product design and engineering, manufacturing, marketing and sales, and information systems) as well as beyond the organizational boundaries (at the very least,

[3] Jafari et al. (2022) drew upon ROT to address the question of whether MCC mediates the relationship between supply integration and firm performance, not to explain and predict MCC.

with customers). On the one hand, our comprehensive, systematic, and detailed presentation of the mechanisms whereby KAfC, PM, and OSCU mutually facilitate their implementation and reciprocally reinforce their benefits in the pursuit of MCC, along with the illustration of these mechanisms by means of company case examples (see Appendices 2 and 3), offers several selling points to managers advocating a holistic approach to the implementation of these practices. On the other hand, possible resistance from customers to sharing information on their product preferences/experiences could be reduced by the promise—corroborated by our empirical findings—of greater product flexibility without compromising on cost, quality, or delivery.

Limitations and Related Research Opportunities

The present study has some limitations that can be overcome in future research. First, this paper focuses on practices that map one-to-one onto the fundamental building blocks of mass customization identified by Salvador et al. (2009) but does not fully cover them because of data unavailability. Future research could develop comprehensive measures of these building blocks and test the research proposition—suggested by our results—that these building blocks should be created simultaneously rather than sequentially. Similarly, richer data would allow future studies to empirically examine the effectiveness of the proposed bundle of practices for different degrees of product customization, corresponding to different mass customization strategies, or the role that sales configurator characteristics, such as user-friendliness, are likely to play in strengthening the synergies among these practices in the pursuit of MCC. Another focus for future research could be the effect of complementing this bundle of practices with cybersecurity systems aimed at mitigating data protection concerns about capturing and storing rich customer information as part of an organization's KAfC.

Second, the present study, while presenting compelling arguments and robust evidence supporting the simultaneous implementation of KAfC, PM, and OSCU to improve MCC, does not address the question of how managers can implement these practices simultaneously. While answering this "how" question will most likely require qualitative research, we can safely conjecture that human resources will play an important role in this process. This is because the resource orchestration literature has explicitly recognized that "multiple levels of management, with different perspectives and pressures, must cooperate" (Chadwick et al., 2015, p. 361) to orchestrate resources. However, research on the micro-foundations of resource orchestration is still in its infancy (Symeonidou & Nicolaou, 2018) and, likewise, there is little prior research on the individual-level enablers of MCC (Trentin et al., 2019). Future studies could not only address these gaps but also complement the results of previous studies on the crucial role played by human resources in linking competitiveness and environmental sustainability (e.g., Almanza Floyd et al., 2024) and on the ways in which several dimensions of firm performance are affected by human resource-related factors, such as leadership style (e.g., Dimple & Tripathi, 2024; Prabhu & Srivastava, 2023), top management team characteristics (e.g., De la Gala-Velásquez et al., 2023), and human resource flexibility (e.g., Dimple & Tripathi, 2024).

Future research could also apply a higher level of analysis than the organization level adopted in the current research. This is because the simultaneous increase in KAfC, PM, and OSCU requires information exchange and collaboration not only within but also beyond organizational boundaries. Thus, research on digital platform–based ecosystems (see Helfat & Raubitschek, 2018; Suzic & Chatzimichailidou, 2023), Industry 4.0 technologies (e.g., Pandey et al., 2024; Srivastava & Bag, 2023), and stakeholder engagement (see D'Adamo, 2023; D'Adamo et al., 2024; Kujala et al., 2022) might generate additional insights into how to carry out this coordinated move.

We also recognize the need for additional research on the extent to which our findings can be extended to industries not covered by our sample. Finally, we underscore that the cross-sectional nature of our data has led us to formulate our hypothesis in correlational terms and, certainly, a causal interpretation of our empirical findings is not recommended. However, our conceptual arguments support the causal effect of the bundling of KAfC, PM, and OSCU on MCC, and this causal effect could be tested by future longitudinal studies.

Conclusions

The present study joins the stream of research on how to reconcile product flexibility with other dimensions of operational performance, that is, how to develop MCC. Prior research has shown that this ambidextrous organizational capability can help companies improve their profitability, foster innovation, and transition toward sustainable production. However, prior research has also shown that developing MCC is a complex endeavor that requires putting multiple enablers in place, and that uneven or interrupted paths toward this goal are not unusual. To develop guidelines capable of supporting companies engaged in this challenging process, it is crucial to understand the relationships between MCC enablers and how these relationships affect MCC, as firms implementing mass customization must decide not only what enablers to implement but also in what sequence.

The present study adds to the relatively limited body of knowledge on these issues. It does so by conceptually and empirically investigating, for the first time, the added value of bundling three organizational practices (i.e., KAfC, PM, and OSCU) that map one-to-one onto the fundamental building blocks of mass customization identified by prior, influential research. Our conceptual and empirical results consistently support a holistic approach to the implementation of these practices, as advancements in the implementation of each of them are facilitated and made more effective by advancements in the implementation of the other two. Theoretically, these results have a bearing on how the effects of these practices on MCC should be modeled to better explain and predict a manufacturer's MCC, at least in the industries covered by our sample. Pragmatically, our results suggest a specific path to improving MCC—a path that challenges the mainly sequential logic that dominates the literature on the guidelines for the implementation of mass customization—and offer several selling points to managers striving to overcome resistance to this specific path. Overall, the present study supports flexible systems management by enriching the body of knowledge on how to create a system capable of reconciling product flexibility with low cost, fast delivery, and high quality.

Appendix 1: Prior Research Results on the Relationships between MCC Enablers Whose Definitions Conceptually Overlap with Two or More of the Focal Organizational Practices

Several studies on the enablers of MCC have explicitly or implicitly suggested relationships among constructs whose definitions overlap to various extents with KAfC, PM, and OSCU. However, none of these studies has focused on the effect on MCC of bundling exactly KAfC, PM, and OSCU.

Source	MCC enabler overlapping with PM or KAfC or OSCU (formal conceptual definition)	Conceptual overlap with… (justification)	Results relevant to the present study
Zipkin (2001)	*Elicitation* ("Any elicitation process is an artful means of leading customers through the process of identifying exactly what they want. And it reduces the costs associated with customers' laborious searching." (Zipkin, 2001, p. 82))	*OSCU* ("mass customization usually employs the computer and the Internet. Advances in user interfaces now make it possible, fairly cheaply and quickly, to construct a program to guide customers or salespeople through an array of choices." (Zipkin, 2001, p. 83))	No explicit hypothesis concerning the interplay among MCC enablers For a mass customization system to work, elicitation and process flexibility, besides logistics, "must be linked tightly to form a coherent, integrated whole" (Zipkin, 2001, p. 84)
	Process flexibility ("a high-volume but flexible process [that] translates [customer-specific] information into the physical product" (Zipkin, 2001, p. 83))	*PM* ("Flexibility-enhancing innovations range from modular design and lean operations to the increasing use of digital-information technology for controlling manufacturing equipment" (Zipkin, 2001, p. 83))	
Tu et al. (2004)	*Customer closeness* ("the practice of keeping close contact with customers, to communicate with customers effectively, and to understand customers' individual needs" (Tu et al., 2004, p. 150))	*KAfC* (understanding customers' needs entails the acquisition and assimilation of customer knowledge)	Large-scale empirical support for the hypothesis that: "Firms that are closer to customers will have higher levels of modularity-based manufacturing practices" (Tu et al., 2004, p. 153)
	Modularity-based manufacturing practices (second-order construct reflected by product modularity, process modularity and dynamic teaming. "*Product Modularity* is the practice of using standardized product modules so they can be easily reassembled/rearranged into different functional forms, or shared across different product lines" (Tu et al., 2004, p. 151))	*PM* (by its definition, the second-order construct termed modularity-based manufacturing practices includes PM)	

continued

Source	MCC enabler overlapping with PM or KAfC or OSCU (formal conceptual definition)	Conceptual overlap with… (justification)	Results relevant to the present study
Salvador et al. (2009)	*Solution space development* (the ability to "identify the idiosyncratic needs of its customers, specifically, the product attributes along which customer needs diverge the most […] Once that information is known and understood, a business can define its 'solution space,' clearly delineating what it will offer — and what it will not" (Salvador et al., 2009, p. 72))	*KAfC* (by its definition, solution space development implies the acquisition, assimilation and exploitation of customer knowledge)	"A company might decide to improve all three capabilities simultaneously or, rather, to prioritize one or two of them" (Salvador et al., 2009, p. 76)
	Robust process design (the ability to "reuse or recombine existing organizational and value-chain resources to fulfill a stream of differentiated customer needs" (Salvador et al., 2009, p. 73))	*PM* (enables a company to create product variety in a combinatorial fashion from a relatively small number of components (Ulrich, 1995))	
	Choice navigation (the ability to "support customers in identifying their problems and solutions while minimizing complexity and the burden of choice" (Salvador et al., 2009, p. 74))	*OSCU* (enables a company to give customers the freedom to explore its solution space, ideally in a flexible and focused manner, and to make their choices within the constraints specified by the company (Trentin et al., 2013))	
Peng et al. (2011)	*Modular product design* ("Modular product design allows firms to de-construct a product and its underlying production processes based on a formal product architecture, which subsequently allows one to reconfigure those underlying components into new products and associated processes" (Peng et al., 2011, p. 1027))	*PM* (by its definition, modular product design includes PM)	Large-scale empirical support for the hypothesis that: "Modular product design is positively associated with product configurator IT" (Peng et al., 2011, p. 1029)
	Product configurator IT ("[information technology] tools made available to customers and salespeople to let them participate in activities related to the co-design of a product, and to guide customers through the process of designing a product" (Peng et al., 2011, p. 1027))	*OSCU* (by its definition, product configurator IT includes an online sales configurator)	
Zhang et al. (2015a)	*Elicitation* ("Elicitation refers to 'a mechanism for interacting with the customer and obtaining specific information' (Zipkin, 2001, 82)" (Zhang et al., 2015a, p. 461))	*OSCU* (see the observations made above concerning Zipkin, 2001)	Large-scale empirical support for the hypotheses that elicitation positively affect process-flexible technology and vice versa
	Process-flexible technology ("process-flexible technology, refers to a 'production technology that fabricates the product according to the information' (Zipkin, 2001, 82)" (Zhang et al., 2015a, p. 462))	*PM* (see the observations made above concerning Zipkin, 2001)	

continued

Source	MCC enabler overlapping with PM or KAfC or OSCU (formal conceptual definition)	Conceptual overlap with… (justification)	Results relevant to the present study
Salvador et al. (2015)	*Customer involvement* ("the extent to which a manufacturer engages in interactions with its customers to understand and respond to their needs and to receive feedback on quality and delivery" (Salvador et al., 2015, p. 619))	*KAfC* (by its definition, customer involvement entails the acquisition, assimilation and exploitation of customer knowledge)	Empirical support for the pairwise complementarity effects of customer involvement, flexible manufacturing resources, and product management tools on MCC. Lack of empirical support for their three-way complementary effect on MCC[a]
	Flexible manufacturing resources ("the aggregate availability of machines, production workers, product architectures, process architectures, and suppliers that are flexible" (Salvador et al., 2015, p. 622))	*PM* (is one of the five first-order constructs that form the second-order construct termed flexible manufacturing resources)	
	Product management tools ("IT [information technology] and software applications that the plant personnel utilize to support decision making and monitor information related to the configuration, the manufacturing, and the delivery performance of products" (Salvador et al., 2015, p. 619))	*OSCU* (one of the three first-order constructs that form the second-order construct termed product management tools is product configurator, which includes a sales configurator to "acquire complete and nonconflicting customer specifications" (Salvador et al., 2015, p. 619))	
Purohit et al. (2016)	*Modularity-based practices* ("an attribute of the product system that characterises the ability to mix and match independent and interchangeable product building blocks with standardised interfaces in order to create product variants" (Purohit et al., 2016, p. 776))	*PM* (by its definition, the notion of modularity-based practices coincides with PM)	Modularity-based practices strongly drive the use of web-based interactive systems but weakly depend on the latter
	Web-based interactive systems ("online product configurator, interface among SC [supply chain] partners" (Purohit et al., 2016, p. 776))	*OSCU* (by their definition, web-based interactive systems include online sales configurators)	
Suzić et al. (2018)	*Product platform development* ("defining a set of design parameters (features, components, etc.) that form a common structure from which a stream of derivative products (product family/families) can be efficiently developed and produced" (Suzić et al., 2018, p. 871))	*PM* ("PP [product platform development] embeds M [product modularization]" (Suzić et al., 2018, p. 860))	"Figure 2. Resulting model of enabler relationships derived from the analysis of articles." (Suzić et al., 2018, p. 871) The model depicted in this figure suggests that product platform development be implemented before IT-based product configuration
	Information technology (IT)-based product configuration ("a set of IT-backed activities that support order acquisition and fulfilment by translating each customer's specific needs into correct and complete product information" (Suzić et al., 2018, p. 871))	*OSCU* (IT-based product configuration includes OSCU, as it "guides users in defining feasible product variants which satisfy his/her needs, supplies users with real-time information on the overall characteristics of the product configuration" (Suzić et al., 2018, p. 871))	

[a]Flexible manufacturing resources and product management tools are second-order constructs of formative nature and, therefore, the first-order constructs underlying each of these two higher-order constructs are not expected to co-vary (see Jarvis et al., 2003). This implies that (Salvador et al. 2015)'s empirical results on the three-way complementarity of customer involvement, flexible manufacturing resources and product management tools cannot be extended to the constructs underlying the last two variables. Doing this would be an instance of ecological fallacy, according to (Certo et al. 2017) definition: to "mistakenly assume that a relationship at one level mirrors the relationship at another level" (p. 1538)

Appendix 2: Mechanisms Whereby PM, KAfC, and OSCU Mutually Facilitate Their Implementation in the Pursuit of MCC

There are several mechanisms whereby PM, KAfC, and OSCU mutually facilitate their implementation. These mechanisms contribute to explaining why MCC is better predicted by the joint presence of these three practices than by the same practices considered in isolation.

Product modularity facilitates both KAfC and OSCU There are two reasons why PM facilitates KAfC: First, it minimizes the number of product components affected by changes in customers' functional requirements (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). As a result, knowledge about these changes can be incorporated into new product solutions more quickly and at a lower cost (Ulrich, 1995). Second, PM increases component commonality across product solutions (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). As a consequence, knowledge acquired from one customer with regard to a specific solution can be incorporated into other solutions more easily (Wang et al., 2014). For instance, following requests from a few customers, a carwash equipment manufacturer developed a new module that mixes detergent with air, which not only produces foam, as requested by those customers, but also reduces detergent consumption. This product innovation was immediately shared among other solutions of the same manufacturer thanks to their modular architecture.

Likewise, there are two mechanisms whereby PM facilitates OSCU: One is by simplifying the "dynamic pricing" of the product (Tseng & Piller, 2003, p. 11), meant as the dynamic generation of the product price based on the answers provided by a customer during the sales dialogue.[4] This is a consequence of the fact that in a fully modular product, the different product attributes that a customer can customize are mapped onto distinct physical components (Ulrich, 1995). This allows the association of each possible value of each customizable attribute with a specific price. In turn, this enables the configurator to compute the price of the configured product by simply adding up the prices associated with the answers provided by the customer during the sales dialogue (Forza & Salvador, 2006), as illustrated by Dell workstations (Dell.com). This is a quick approach, which does not require implementing the so-called generic bill of materials to determine the cost of the configured solution and then applying a markup (Forza & Salvador, 2006). Furthermore, this approach simplifies price updating, as prices are directly linked to the possible answers in the sales dialogue and can be modified without having to update the costs of materials and the costs of production activities in the respective master files (Forza & Salvador, 2006). In summary, PM facilitates OSCU by reducing the effort needed to define and maintain the pricing model of an online sales configurator. Another mechanism whereby PM facilitates OSCU is observed whenever the product under consideration needs to be specified by at least some of its target customers in terms of functions rather than of product components, as often happens especially for complex products (see Felfernig et al., 2001). If this is the case, a functional view of the product must be codified in the sales configuration model underlying the sales dialogue. Notably, the creation of this "function structure," which represents the product's functions and their interconnections, is also a fundamental step in the definition of a modular product architecture (Ulrich, 1995, p. 421). Thus, PM facilitates OSCU also by sharing with the latter the costs of defining and maintaining a functional view of the product.

Online-sales-configurator use facilitates both KAfC and PM There are two mechanisms whereby OSCU facilitates KAfC: One is by enabling a systematic analysis of past product configurations and customers' clickstream data. For example, a systematic analysis of clickstream data can provide information about product solutions that have been evaluated but not ordered, thus ultimately leading to a refined solution space (Salvador et al., 2009). The other mechanism is by freeing resources in the technical office (Hvam et al., 2013) thanks to both the elimination of sales configuration errors and the reduction of the risk of unnecessarily developing ad hoc solutions (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). The resources thus freed can be invested in the assimilation and exploitation of knowledge from customers, thereby reducing the necessity of procuring additional resources to increase KAfC. At a manufacturer of mold bases for plastic injection molding, for example, OSCU eliminated configuration errors in the tendering phase and, consequently, freed the time that was previously spent in the technical office to correct bills of materials and production sequences. The resources thus freed helped improve the company's KAfC, as witnessed by the subsequent development of new product solutions that better satisfied the needs of certain target markets.

As for the mechanism whereby OSCU facilitates PM, this revolves around the creation of a product's function structure. As mentioned above, a functional view of the product must be codified in the sales configuration model

[4] This dialogue guides customers to progressively specify the values of all the product attributes that can be customized and prevents customers from defining inconsistent or invalid values thanks to the constraints that are included in the logic structure—the sales or commercial model—behind that dialogue (Forza & Salvador, 2006).

whenever the product needs to be specified by at least some of its target customers in terms of functions. At the same time, as mentioned above, the creation of a product's function structure is a fundamental step in the definition of a modular product architecture. Thus, OSCU and PM facilitate one another by sharing the costs of defining and maintaining a functional view of the product.

Knowledge absorption from customers facilitates both PM and OSCU Product modularity is facilitated by KAfC because the latter helps a manufacturer keep its solution space aligned with its customers' evolving needs. This reduces technical personnel's workload for ad hoc engineering (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"), and the resources thus freed can be employed to improve PM. For instance, at a manufacturer of electric linear actuators, the workload for ad hoc engineering in the technical office had become excessive due to the acquisition of new customers who demanded the same operating ranges provided by their previous suppliers. The company developed a routine—revolving around customers' compiling of a detailed technical form—aimed at understanding for which applications customers were demanding a certain operating range and, therefore, whether they really needed an ad hoc solution or would be equally satisfied by a predefined solution with a different operating range. This improvement in the company's KAfC reduced the number of customer orders requiring ad hoc engineering. The resources thus freed in the technical office were employed to increase the combinability of the product's functional modules, thereby achieving a higher degree of PM.

Finally, KAfC facilitates OSCU because the ability to elicit adequate information from customers, to assimilate it and to apply it in the implementation of an online sales configurator leads to fewer trial-and-error loops in the development of a configurator that suits its target users (Hvam et al., 2008). For example, it is easier to implement a sales configurator capable of explaining the benefits of the various choice options in a way that reduces both cognitive complexity and anticipated regret in target customers' decision processes (Trentin et al., 2013). Clearly, such a configurator will be more easily accepted by its target users (Haug et al., 2019), and this will lead to a higher level of OSCU.

Appendix 3: Mechanisms Whereby PM, KAfC, and OSCU Mutually Reinforce Their Benefits in the Pursuit of MCC

There are several mechanisms whereby PM, KAfC, and OSCU mutually reinforce their benefits in the pursuit of MCC. These complementarity mechanisms contribute to explaining why MCC is better predicted by the joint presence of these three practices than by the same practices considered in isolation. While there is a common rationale behind all these mechanisms (that is, each practice contributes to realizing the potential MCC benefits of the other two to a larger extent), the individual mechanisms are idiosyncratic in their details and, therefore, deserve to be presented separately.

OSCU reinforces the positive effect on MCC of both KAfC and PM Knowledge absorption from customers helps manufacturers define and maintain a solution space that adequately reflects their target customers' idiosyncratic needs over time. Such a solution space is a prerequisite to fulfilling those needs by means of predefined solutions instead of ad hoc solutions, thus achieving higher MCC (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). However, the improvement of MCC does not fully materialize if customers are offered, instead of the predefined solutions that fully meet their needs, either predefined solutions that fit their needs worse or solutions that require ad hoc engineering. This could happen because the salesperson serving a customer has not been informed of, or has forgotten about, the existence of the predefined solution that best fits the customer's needs (Salvador & Forza, 2004). Since OSCU reduces the risk of this occurring (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"), OSCU helps manufacturers get the most out of KAfC in terms of MCC improvement. At a manufacturer of carwash equipment, for instance, OSCU ensured that customers were offered a few innovative solutions (e.g., forward arrow signal lamps equipped with high-luminosity light-emitting diodes) that best fitted their specific needs and were available in the company's solution space but were often overlooked by salespeople because of the little attention these people usually paid to little product improvements.

Likewise, OSCU helps manufacturers fully exploit the potential benefits of PM in enhancing MCC. These potential benefits get lost, at least in part, whenever a customer's order is fulfilled with an ad hoc solution despite the availability of a suitable solution in the predefined, modular solution space. Again, the risk of this occurring is lowered by OSCU (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). At the carwash equipment manufacturer mentioned above, for example, OSCU contributed to decreasing the number of customer orders fulfilled with engineered-to-order products by 90% in 3 years. This helped the company take full advantage of the modular product architecture of its predefined solutions.

PM reinforces the positive effect on MCC of both OSCU and KAfC Online sales configurator use has the potential for improving MCC through the reduction in the number of customer orders fulfilled with engineered-to-order products (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"). This potential benefit, however, does not materialize if a customer using the online sales configurator fails to create an acceptable product configuration within the solution space and for this reason demands ad hoc engineering. The risk of this occurring is reduced by PM, as the latter makes it easier to develop an online sales configurator that enables its users to change the choice made at any previous step of the configuration process without having to start it over again.[5] As a result, customers can conduct more trial-and-error tests to evaluate the effects of their initial choices and improve upon them during the time span they are willing to devote to the configuration task (Trentin et al., 2013).

The same logic explains why PM helps manufacturers get the most out of KAfC to improve MCC. Defining and maintaining a solution space that adequately reflects customers' idiosyncratic needs over time, thanks to KAfC, might not be sufficient to reduce the number of customer orders fulfilled with engineered-to-order products. If customers fail to identify an acceptable product solution within the solution space, despite the existence of such a solution, they may end up requiring an ad hoc solution. The risk of this occurring is reduced by PM, as the free combinability of choice options facilitates trial-and-error experimentation within the solution space, as explained above.

KAfC reinforces the positive effect on MCC of both OSCU and PM The mechanisms whereby OSCU may improve MCC (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks") are inhibited whenever a customer is not satisfied with the solution space modeled in the online sales configurator and, hence, demands an ad hoc solution. Since KAfC reduces the risk of this occurring (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks"), KAfC works as a catalyst for these mechanisms. This is well illustrated by the manufacturer of carwash equipment mentioned above. This company embarked on the implementation of a sales configurator without the resources needed to effectively survey target customers' needs. As a result, the solution space initially modeled in the configurator was inadequate, as witnessed by the fact that the first two customer orders processed after the implementation of the configurator required ad hoc engineering and did not benefit at all from OSCU. This experience prompted the company's decision to improve its KAfC.

Similarly, the mechanisms whereby PM may enhance MCC (see the section titled "Focal Organizational Practices and Their Mapping onto Mass Customization Building Blocks") are inhibited if customers demand ad hoc solutions that cannot be easily derived from the extant modular architecture (Salvador et al., 2020). Accordingly, prior research has repeatedly recommended that PM be based on a thorough understanding of customer needs (e.g., Tu et al., 2004). In other words, to fully exploit the potential benefits of PM in enhancing MCC, KAfC is a prerequisite.

[5] This is because the essential design principle for a modular product architecture is that every product component must specialize in fulfilling a specific function and can be altered without affecting the other components (Ulrich, 1995).

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Declarations

Conflict of interest The authors declare no competing interests.

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Key Questions

1. How can manufacturers create flexible systems that are able to provide customized products without compromising cost, delivery, or quality?
2. For manufacturers pursuing this goal, what is the added value of bundling three, long recommended, mass customization practices? Conversely, what are the risks of implementing only a subset of these practices or of implementing them in some sequence?
3. How can managers overcome resistance to a holistic approach in the implementation of these practices? How can human resource management, stakeholder engagement, and digitalization facilitate this coordinated move?
4. How is the research stream on mass customization related to that on manufacturing and supply chain flexibility?

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Alessio Trentin is an assistant professor of Management Engineering at the University of Padova (Italy). His research interests focus on mass customization, its antecedents and its consequences, embracing topics such as form postponement, product configuration, organization-level and individual-level enablers of mass customization, the interplay of mass customization with country-of-origin strategies and with environmental sustainability, and mass customization implementation guidelines. He has (co)authored more than 60 publications, of which 22 published in international peer-reviewed journals, including the *International Journal of Operations & Production Management* (IJOPM), the *International Journal of Production Economics*, the *International Journal of Production Research, Production Planning & Control, Computers in Industry*, and *Industrial Management & Data Systems*, and his current h-index is 17 (15) in Scopus (Web of Science) database. At the 23rd international EurOMA conference, he was awarded the "2016 Harry Boer Highly Commended Award", supported by Emerald and IJOPM. He participated in mass customization-related research projects funded by several organizations, including the European Union and the Zaragoza Logistics Center (Spain), a joint research center of MIT (US) and Aragona government (Spain). Since 2014, he has served on the scientific committee of the International Conference on Mass Customization and Personalization - Community of Europe.

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