

# **Balancing Modularity and Solution Space Freedom Effects on Organisational Learning and Sustainable Innovation**

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*Document Version*

Final published version

*Published in:*

International Journal of Production Research

*DOI:*

[10.1080/00207543.2018.1458165](https://doi.org/10.1080/00207543.2018.1458165)

*Publication date:*

2018

*License*

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*Citation for published version (APA):*

Vos, M. A., Raassens, N., Van der Borgh, M., & Nijssen, E. J. (2018). Balancing Modularity and Solution Space Freedom: Effects on Organisational Learning and Sustainable Innovation. *International Journal of Production Research*, 56(20), 6658-6677. <https://doi.org/10.1080/00207543.2018.1458165>

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To cite this article: Maren A. Vos, Néomie Raassens, Michel van der Borgh & Edwin J. Nijssen (2018) Balancing modularity and solution space freedom: effects on organisational learning and sustainable innovation, International Journal of Production Research, 56:20, 6658-6677, DOI: 10.1080/00207543.2018.1458165

To link to this article: <https://doi.org/10.1080/00207543.2018.1458165>



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Published online: 04 Apr 2018.



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## Balancing modularity and solution space freedom: effects on organisational learning and sustainable innovation

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(Received 31 March 2017; accepted 19 March 2018)

Many technology-intensive (TI) firms find it challenging to leverage customisation and achieve sustainable innovation. Although some firms use modularity to tackle this challenge, mixed effects on sustainable innovation have been reported. This study uses organisational learning and ambidexterity theory to provide insights into how TI firms can achieve ‘win-win’ situations where sustainable innovation is increased through customisation. First, we argue that customisation should be viewed two-dimensionally and identify both modularity and solution space freedom as important dimensions. We argue that modularity reflects knowledge specialisation and solution space freedom reflects knowledge variety. Both of these dimensions affect organisational learning and, in turn, sustainable innovation. Second, we argue that the relationship between customisation and organisational learning is affected by supplier characteristics, specifically supplier sophistication. Survey data from 166 managers were used to empirically test the conceptual model and hypotheses. Polynomial response surface analysis confirms that customising by balancing high degrees of both modularity and solution space freedom results in superior organisational learning. High levels of supplier sophistication do not strengthen these effects. Rather, our results show that combining high degrees of modularity with constrained solution spaces increases learning for TI firms working with less sophisticated suppliers. In addition, organisational learning fully mediates the effect of customisation on sustainable product and process innovation.

**Keywords:** modularity; solution space; customisation; organisational learning; sustainable innovation

### Introduction

To adapt to global competitive pressures, firms must accommodate heterogeneous customer needs while mitigating the ecological and environmental impact (Boër et al. 2013; Medini, Da Cunha, and Bernard 2015). On the one hand, the consumerisation of business-to-business (B2B) buying results in customers insisting on complex solutions against lower costs (Davie, Stephenson, and De Uster 2010; Lingqvist, Plotkin, and Stanley 2015). On the other hand, increasing global environmental concerns prompt firms to pay more attention to sustainable innovation, i.e. creating or improving products and processes to contribute to the ecological environment (Boons et al. 2013; Chen, Lai, and Wen 2006; Fiksel et al. 2014; Flores et al. 2008; Foxon and Pearson 2008). While firms have to pursue both customisation and sustainable innovation to remain competitive (Boër et al. 2013; Medini, Da Cunha, and Bernard 2015), pursuing both of these goals jointly is perceived as being very difficult (Boër et al. 2013).

The manufacturing paradigms of customisation and sustainable innovation are frequently referred to in the literature, yet mainly treated in isolation. Recent research has brought the two paradigms together and has proposed to simultaneously model customisation and sustainability (e.g. Boër et al. 2013; Medini, Da Cunha, and Bernard 2015). However, the way that customisation affects firms’ sustainability remains open to debate (Boër et al. 2013; Pourabdollahian, Taisch, and Piller 2014; Medini, Da Cunha, and Bernard 2015). Firms could deploy modularity to resolve the difficulty of simultaneously pursuing customisation and sustainable innovation (Chen, Lai, and Wen 2006; Davies, Brady, and Hobday 2007; Tang, Wang, and Ullah 2017), because modularity may enhance flexibility and sustainable product development (Ülkü and Hsuan 2017). However, modularity can also add variety to the operative resources needed (Raddats et al. 2016), which negatively affects firms’ environmental impact (Medini, Da Cunha, and Bernard 2015). Against this backdrop, the goal of this research is to understand the relationship between customisation and sustainable innovation. In particular, this study argues that pursuing both customisation and sustainable innovation does not necessarily imply a trade-off. Rather, the pursuit of customisation can increase sustainable innovation.

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We contribute to the existing literature in three ways. First, we suggest that customisation should not be viewed one-dimensionally, i.e. as two ends of a spectrum with standardisation on one end and pure customisation on the other (see Lyons et al. 2013 for an overview) but rather two-dimensionally (cf. Duray et al. 2000). Specifically, we propose that customisation captures the degree of modularity and solution space freedom the firm has adopted. The degree of modularity refers to the extent to which the constituent functional subparts (i.e. modules) of a solution can be developed independently and can easily be configured to function together as a whole (Ulrich 1995; Ghosh, Dutta, and Stremersch 2006; Baldwin and Henkel 2015). Firms that customise through higher degrees of modularity are able to offer more flexible configurations to their customers (Tang, Wang, and Ullah 2017). The degree of solution space freedom determines whether the solution's design can be adjusted to meet specific customer needs (Duray et al. 2000; Steiner 2014; Medini, Da Cunha, and Bernard 2015). Business customers in technology-intensive (TI) industries often demand additional engineering and design changes (Davies et al. 2011; Egelman et al. 2017). For example, a customer might ask a semiconductor firm to develop a new (part of a) machine with very specific positioning systems at higher speeds, or to incorporate a new polishing technique into the system. TI firms that allow high degrees of solution space freedom accommodate these requests, while TI firms with constrained solution spaces only accommodate requests with predefined functionalities. Together, the two dimensions determine the customisation approach a firm pursues. We contribute to the literature on modularity and customisation (e.g. Ulrich 1995; Duray et al. 2000; Ghosh, Dutta, and Stremersch 2006; Baldwin and Henkel 2015; Tang, Wang, and Ullah 2017) by showing that modularity indeed interacts with the accommodation of design changes by TI firms (Furlan, Cabigiosu, and Camuffo 2014). Furthermore, we validate and extend earlier research by Lyons et al. (2013) and show that our conceptualisation allows for a more fine-grained and appropriate categorisation of customisation, particularly for TI firms.

Second, in line with Adler, Goldoftas, and Levine (1999) and Markides (2013), we propose that the challenge of simultaneously managing both routine (i.e. modularity) and nonroutine tasks (i.e. solution space freedom) can be framed as an ambidexterity challenge. Therefore, we use ideas and concepts from the ambidexterity literature to examine the effects of customisation (cf. Markides 2013). Drawing on the ambidexterity literature and organisational learning theory, we propose that customisation affects firms' organisational learning processes (cf. Wiersma 2007; Egelman et al. 2017), which then drives their sustainable innovation (Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016). In particular, we argue that the level of organisational learning depends on the alignment or non-alignment of modularity and solution space freedom. TI firms that align modularity and solution space freedom effectively are ambidextrous. TI firms that do not align these dimensions focus on either solution space freedom or modularity. To detect how (non-)alignment affects organisational learning, we employ polynomial regression analysis and three-dimensional response surface plots (Edwards and Parry 1993). Our findings contribute to research that proposes that modularity functions as a mechanism for problem solving and knowledge management (Mikkola 2003; Brusoni et al. 2007; D'Adderio and Pollock 2014; Baldwin and Henkel 2015). They also attest to the synergy effects of modularity with solution space freedom on organisational learning by showing that these dimensions can be supportive or complementary to each other.

Third, this paper contributes to research on supply chain management and the role of modularity in supply chains (Zhang, Huang, and Rungtusanatham 2008; Piran et al. 2016). When conditions in the downstream market (i.e. customisation) create a need for flexibility, more demands are placed on upstream supplier relationships (Wathne and Heide 2004). While the supply chain literature offers ideas on how customisation, and modularity in particular, might affect the supply chain (e.g. Brusoni and Prencipe 2001; Boër et al. 2013), there is scant empirical validation of the role of suppliers when firms customise. Building on knowledge theory, we argue that customisation poses a coordination problem (Wang et al. 2017) between the firm and its suppliers, where the firm needs to co-ordinate both internal and external information flows (Gulati and Singh 1998). The amount and quality of supplier knowledge determine the effectiveness of knowledge transfer (Azadegan and Dooley 2010). Therefore, we argue that TI firms' learning mechanisms are affected by the sophistication of their suppliers, i.e. suppliers' technical competencies and their ability to share knowledge and innovate (Azadegan and Dooley 2010; Eggers et al. 2017). This study extends the above mentioned literature by moving from a simplistic understanding (i.e. 'suppliers are important') to a more nuanced model that incorporates high and low supplier sophistication.

From a managerial perspective, determining how customisation affects organisational learning and, in turn, sustainable innovation provides insights into whether and how TI firms should go about implementing a customisation approach. In using our two-dimensional conceptualisation, managers learn how to leverage customisation to develop sustainable innovations. Moreover, this study identifies an additional criterion for supplier selection, namely supplier sophistication. While we do not believe that supplier sophistication will surpass basic issues of cost, quality and performance, supplier sophistication may be an important consideration for TI firms that pursue (non-)alignment and aim to increase organisational learning.

The remainder of this study is organised as follows. We begin by presenting our conceptual framework and hypotheses. We then describe the research methodology used to test the hypotheses and present the empirical results. Finally, we discuss the theoretical and managerial implications and the study's limitations, and we outline avenues for future research.

### Conceptual framework

The primary purpose of this study is to empirically examine the relationships between customisation (i.e. different combinations of modularity and solution space freedom), organisational learning, and sustainable innovation while taking into account supplier sophistication. Figure 1 summarises our conceptual framework. We develop the core concepts, model and hypotheses below.

#### *Customisation through modularity and solution space freedom*

Customisation is aimed at creating unique value for individual customers (Wang et al. 2017) and can be defined as the degree to which a firm's solution is adapted to meet specific customer needs (Fornell et al. 1996, 9). Modularity is a key enabler of customisation (Duray et al. 2000). It enables components to be flexibly combined to provide high variety (Worren, Moore, and Cardona 2002), which allows firms to configure different solutions. Because high degrees of modularity often imply that modules cannot change outside of a predefined range (Sanchez and Mahoney 1996), customisation is offered through a predefined set of options. Thus, while modularity offers customers some level of choice, it does not offer individual customers the option to request a completely specific solution. However, true customisation allows customers to specify all key attributes of a solution (Duray et al. 2000; Lyons et al. 2013). Therefore, we argue that customisation in TI firms involves two dimensions: the degree of modularity and the degree of solution space freedom.

Solution space freedom refers to the degree to which firms accommodate specific customer requests or changes to designs (Ulrich and Tung 1991; Salvador, De Holan, and Piller 2009; Steiner 2014; Wang et al. 2017). It determines whether functionalities available to solve customer problems are predefined or can be custom designed on demand (Steiner 2014; Medini, Da Cunha, and Bernard 2015). TI firms that fully constrain the solution space choose not to respond to undefined design requests, whereas TI firms with unconstrained solution spaces accommodate custom designs or changes to create solutions completely according to specific customer needs. TI firms can combine various degrees of modularity and solution space freedom, which defines the customisation approach they pursue.

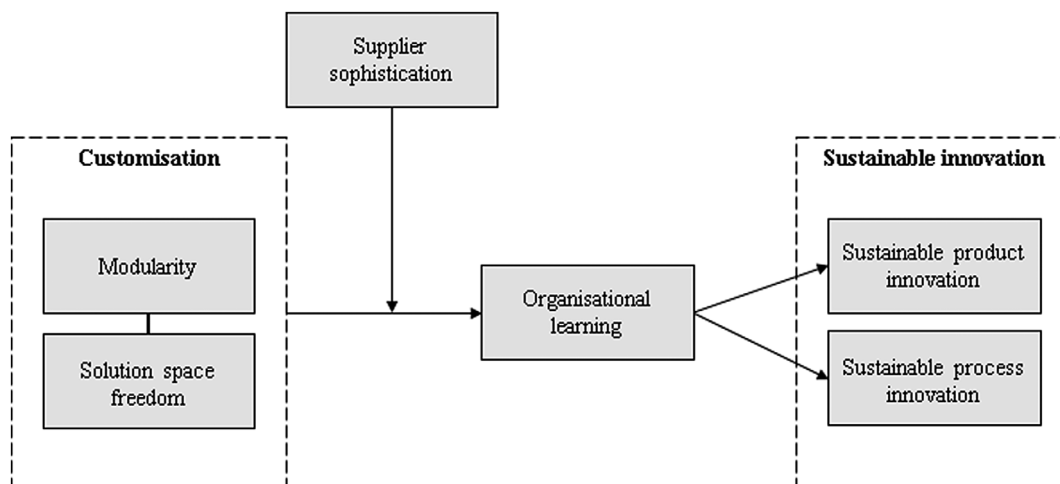


Figure 1. Conceptual framework.

### **Organisational learning**

Organisational learning is defined as ‘the dynamic process of creating new knowledge and transferring it to where it is needed and used, resulting in the creation of new knowledge for later transfer and use’ (Kane and Alavi 2007, 796). It enables firms to extend, modify and reconfigure their existing knowledge (Pavlou and El Sawy 2011) and change their actions through this process. We take an information-processing perspective on organisational learning, whereby information processing involves information acquisition, distribution or interpretation (Huber 1991). Information acquisition is the process of absorbing and storing new information in memory. Information distribution refers to the process of distributing and disseminating relevant information from different sources. Information interpretation is the process by which acquired and distributed information is given one or more commonly understood interpretations (Huber 1991).

It is important to note that organisational learning is conceived as a principal means of achieving strategic renewal. To achieve strategic renewal, firms should explore and create new knowledge while simultaneously exploiting what they already know (Crossan, Lane, and White 1999). Early work on organisational learning has argued that there is a difference between creating new knowledge and using existing knowledge (Cohen and Levinthal 1990). Often, a tension arises between creating new knowledge and using existing knowledge (Crossan, Lane, and White 1999). Therefore, we perceive organisational learning as a dynamic process that occurs both over time and across firm boundaries. Organisational learning is determined to a large extent by the context in which it takes place (Brown and Duguid 1991; Crossan, Lane, and White 1999). We argue that firms learn in accordance with their strategic focus. Our two customisation dimensions represent this strategic focus and thus the internal context. The external context is represented by supplier sophistication.

### **Customisation and organisational learning**

To build our hypotheses, we argue that modularity represents the presence of knowledge specialisation, i.e. gaining cumulative experience in a specific task (Schilling et al. 2003; Narayanan, Balasubramanian, and Swaminathan 2009). Solution space freedom represents the presence of knowledge variety, i.e. exposure to and working on new or different tasks (Staats and Gino 2012). Both knowledge specialisation and variety influence organisational learning (cf. Schilling et al. 2003; Boh, Slaughter, and Espinosa 2007; Narayanan, Balasubramanian, and Swaminathan 2009).

Modularity can be considered as a problem-solving mechanism that divides complex problems into independent or quasi-independent sub-problems (Brusoni et al. 2007). Modules can be separated by their underlying technical knowledge (Baldwin and Henkel 2015). If modules are separated properly, each can be developed by independent specialists inside or outside the organisation (Sanchez and Mahoney 1996; Baldwin and Clark 2000; Robertson, Casali, and Jacobson 2012), or as Brusoni et al. (2007, 122) put it, ‘each module, at the extreme, could become the sole business of specialist firms’. In this case, higher degrees of modularity increase knowledge specialisation (Langlois 2002; Mikkola 2003) and drive firms to pursue specialised learning curves (Schilling 2000). Thus, modularity fuels task differentiation and higher degrees of modularity represent higher levels of knowledge specialisation (Mikkola 2003).

Solution space freedom reflects knowledge variety, i.e. the dispersion of knowledge and experience across distinct problem-solving tasks (Narayanan, Balasubramanian, and Swaminathan 2009). A large variety in problem-solving tasks might stimulate firms to consider more possible knowledge associations (Cohen and Levinthal 1990; Schilling et al. 2003). Many customer-specific requests thus increase knowledge variety (Egelman et al. 2017). Knowledge variety refers to the ability to understand and combine many different knowledge domains to address specific customer requests, which can provide a robust basis for learning (Cohen and Levinthal 1990). TI firms may exploit a pre-defined solution space to solve customer requests, which lowers task and knowledge variety. Alternatively, if the solution space is unconstrained, TI firms work more closely with customers to understand their needs and may explore unknown solutions. This increases knowledge variety across different domains. Thus, higher degrees of solution space freedom represent higher levels of knowledge variety.

Based on Narayanan, Balasubramanian, and Swaminathan (2009), we argue that different combinations of modularity and solution space freedom result in different levels of organisational learning. Figure 2 represents our conceptualisation of TI firms’ customisation approaches based on different degrees of modularity and solution space freedom. Next, we develop our hypotheses. We will focus on alignment and non-alignment of our two dimensions and their impact on organisational learning.

We propose that pursuing both dimensions simultaneously can be framed as an ambidexterity challenge (cf. Adler, Goldoftas, and Levine 1999; Cao, Gedajlovic, and Zhang 2009; Markides 2013), i.e. the challenge of jointly managing knowledge specialisation and knowledge variety. Thus, ambidextrous TI firms align high degrees of modularity and solution space freedom through flexible structures that facilitate task switching (Adler, Goldoftas, and Levine 1999). We



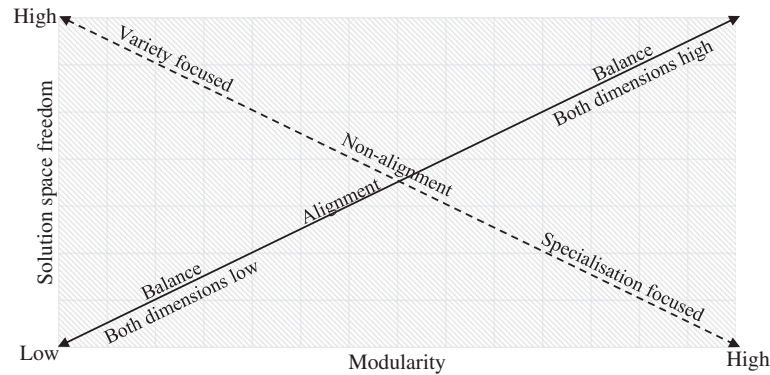


Figure 2. Customisation through (non-)aligning modularity and solution space freedom.

contend that modularity and solution space freedom can be complementary or supportive of one another and argue that each may help leverage the effects of the other (cf. Cao, Gedajlovic, and Zhang 2009). When firms adapt solutions to customer needs, they become more responsive and ensure a constant influx of new, varied knowledge (Schilling et al. 2003; Narayanan, Balasubramanian, and Swaminathan 2009; Staats and Gino 2012). Firm responsiveness minimises the risk of inertia. Solution space freedom thus leverages the positive effects of modularity. In an analogous manner, high degrees of modularity allow ambidextrous firms to leverage the effects of solution space freedom. Modularity offers a framework to systemise the creative processes that arise from unconstrained solution spaces (cf. Adler, Goldoftas, and Levine 1999). This framework may provide the focus needed to increase the benefits gained from knowledge variety (Schilling et al. 2003). Prior research confirms that organisational learning increases when firms combine both knowledge variety and specialisation (Narayanan, Balasubramanian, and Swaminathan 2009; Staats and Gino 2012).

In contrast, low ambidextrous firms align low degrees of modularity and solution space freedom. While the solutions offered by low ambidextrous firms can be scalable (e.g. larger), their designs are predefined and there is minimal configuration. Low ambidextrous firms limit the variety and customer specificity of their solutions to a set of predetermined options, which may negatively affect their ability to incorporate changes and learn (Robertson, Casali, and Jacobson 2012). Based on the above, we propose a linear relationship, such that higher degrees of both modularity and solution space freedom (i.e. high ambidexterity) increase organisational learning. We thus expect a significant, positive slope along the alignment line:

H1a: Organisational learning increases when modularity and solution space freedom increase while remaining in alignment (i.e. as the degree of modularity and solution space freedom are at essentially the same level).

TI firms that do not align modularity and solution space freedom are not ambidextrous. These firms focus on either modularity (i.e. knowledge specialisation) or solution space freedom (i.e. unrelated knowledge variety) and risk inertia or failing to appropriate existing knowledge (cf. Cao, Gedajlovic, and Zhang 2009). TI firms that focus on specialisation combine high degrees of modularity and constrained solution spaces. These firms follow a strategy akin to mass customisation by configuring solutions using predefined functional components (Sanchez 1999) to achieve near mass production efficiency (Pine 1993; Duray et al. 2000; Da Silveira, Borenstein, and Fogliatto 2001; Boër et al. 2013). Although high degrees of modularity increase knowledge specialisation (Langlois 2002; Mikkola 2003), it may also cause inertia and path dependence when the solution space is constrained. Knowledge could become the responsibility of those producing and updating each module, with the results simply combined as 'black boxes' (Robertson, Casali, and Jacobson 2012). Overly specialised knowledge reduces learning possibilities (Brown and Duguid 1991), the development of new capabilities (Schilling et al. 2003) and increases the risk of learning myopia (Boh, Slaughter, and Espinosa 2007; Narayanan, Balasubramanian, and Swaminathan 2009). Thus, firms customising mainly through high degrees of modularity will experience lower levels of organisational learning.

TI firms that customise mainly through solution space freedom may also experience lower levels of organisational learning. These firms accommodate customer-specific requests, but risk assimilating new knowledge without exploiting existing knowledge. Indeed, as knowledge variety increases, these firms are faced with an abundance of unrelated information and forfeit any synergy effects (Schilling et al. 2003). In addition, these firms are often organised around customer requirements specified in unique project orders. Learning often does not occur because the tendency in

project-based organisations is to focus on creating new knowledge without assimilating knowledge, i.e. they get caught up in the 'doing' only (Barron et al. 1998).

Based upon the above reasoning, we expect TI firms that do not align modularity and solution space freedom to be highly susceptible to either inertia or failing to appropriate existing knowledge, which leads to lower levels of organisational learning. Our expectation corresponds to a significant, negative curvature along the non-alignment line. Hence, we hypothesise:

H1b: Organisational learning decreases with rising levels of non-alignment of modularity and solution space freedom.

### ***The moderating role of supplier sophistication***

Much potentially useful knowledge resides outside of the firm (Azadegan and Dooley 2010). To complement their in-house knowledge, TI firms thus need to rely on their suppliers (Brusoni, Prencipe, and Pavitt 2001), an important source of external knowledge (Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016). Based on knowledge management theory, we argue that different customisation approaches require different types of supplier knowledge in order to increase learning. While modularity requires TI firms to mobilise information and knowledge to improve existing designs, solution space freedom encourages TI firms to acquire new knowledge to create new designs. These different knowledge requirements explain the varying abilities of TI firms to benefit from the knowledge of their suppliers. Suppliers can provide two types of knowledge: (1) knowledge that is targeted to the needs and concerns of the focal firm (Cohen and Levinthal 1990) and (2) more innovative, complex knowledge (Azadegan 2011). We propose that the success of (non-) aligning modularity with solution space freedom depends upon the ability of TI firms to access, assimilate and integrate novel or routine knowledge provided by suppliers.

With regard to alignment, TI firms want to maintain their strategic agility by being both aligned to the existing technology (embedded in modules) and adaptive to customer-specific requests. The outsourcing of tasks related to this objective requires particular expertise on the part of the supplier. For example, the supplier should be able to contribute to development, search for diverse alternatives in a large number of solution domains and simultaneously understand the focal firm's existing routines. This expertise is captured by the suppliers' level of sophistication (Primo and Amundson 2002; Azadegan and Dooley 2010; Eggers et al. 2017). Highly sophisticated suppliers are capable of developing and introducing new products and processes (i.e. suppliers are innovative; Azadegan and Dooley 2010) and contribute to problem solving by providing information and delivering quality (Flynn, Schroeder, and Sakakibara 1994; Hartley et al. 1997; Krause, Pagell, and Curkovic 2001). Thus, sophisticated suppliers provide new knowledge focused on improvements, development and innovation (Azadegan 2011). We thus expect that sophisticated suppliers will positively affect organisational learning that accrues from aligning high degrees of modularity and solution space freedom. By contrast, less sophisticated suppliers provide familiar knowledge, as expectations are known and tasks performed are routine-intensive and well-defined (Heide and John 1990; Azadegan 2011). This may even impede the learning effects accruing from alignment. Therefore, we hypothesise:

H2a: The positive effect of aligned and increasing modularity and solution space freedom on organisational learning is stronger for more sophisticated suppliers than for less sophisticated suppliers.

With regard to non-alignment, TI firms risk inertia (in case of a modularity focus) or risk failing to appropriate existing knowledge (when the focus is on solution space freedom). These risks cannot be mitigated by working with sophisticated suppliers, for two reasons. First, when TI firms focus mainly on modularity, they may not be able to integrate knowledge obtained from sophisticated suppliers. Highly sophisticated suppliers are proactive in approaching firms with new technologies and innovations that require non-routine problem-solving and that deviate from existing knowledge (cf. Chen, Li, and Liu 2015). The hierarchy and boundaries created by high degrees of modularity may cause knowledge assimilation problems (Brusoni, Prencipe, and Pavitt 2001; Brusoni and Prencipe 2013; Furlan, Cabigiosu, and Camuffo 2014). Specialised modular structures that substitute inter-organisational information sharing (Cabigiosu and Camuffo 2012) can create 'mental prisons' that prevent TI firms from recognising important changes or contradictory outside knowledge. Moreover, the novel information continuously provided by sophisticated suppliers might disturb the hierarchy corresponding to high degrees of modularity, which inhibits interfirm knowledge exchanges (Furlan, Cabigiosu, and Camuffo 2014). Thus, assimilating highly sophisticated suppliers' knowledge is at odds with customising through high degrees of modularity.



Second, TI firms that focus mainly on solution space freedom will also be unable to benefit from the knowledge of sophisticated suppliers. As Brusoni and Prencipe (2013, 171) argue, ‘within innovation ecosystems, firms must be able to develop heuristics, routines and procedures to change their internal and external patterns of communications, command and information filters’. Achieving this is particularly difficult for TI firms that focus mainly on knowledge variety because these firms continue to approach solutions as one-off efforts. The time and resource constraints that characterise project-based customisation limit the firm’s opportunities for reflection (Sanchez and Mahoney 1996; Barron et al. 1998). Limited reflection makes it difficult to relate to suppliers (Söderlund, Vaagaasar, and Andersen 2008). When sophisticated suppliers continue to provide novel information, the firm’s ability to learn is confounded because the necessary structures will not be formed (Teece, Pisano, and Shuen 1997). Moreover, the one-off nature of projects inhibits firms from developing routines. Once projects end, firms may fail to see the information’s utility for other projects when they lack the necessary structures and routines (Almeida and Soares 2014). These firms reinforce their failure to appropriate existing knowledge. Thus, while highly sophisticated suppliers can be an important source of external knowledge, issues arising from customisation approaches that rely mainly on solution space freedom render this information and knowledge meaningless.

In contrast, low supplier sophistication may mitigate the problems experienced by firms with an overt focus on modularity. These firms use existing knowledge, develop existing skills and focus on the refinement and extension of existing competencies, technologies and paradigms, which continuously improves their resources and processes (cf. Chen, Li, and Liu 2015). These firms may benefit handsomely from collaborating with less sophisticated suppliers because the external knowledge contributes to improving existing operations and solutions. Furthermore, the information structure embedded in interface specifications provides a way to structure tasks (Gomes and Joglekar 2008), which would enable external knowledge to be assimilated when suppliers are less proactive or less capable of knowledge sharing (Cabigiosu and Camuffo 2012). In contrast, TI firms that customise through high degrees of solution space freedom lack the structure to appropriate knowledge from less sophisticated suppliers. These firms lack the framework to systematically accrue and implement any form of external knowledge. In sum, TI firms that focus mainly on solution space freedom will not increase organisational learning via less sophisticated suppliers, though less sophisticated suppliers will positively contribute to the learning mechanisms of firms with high degrees of modularity. Based on the above, we hypothesise:

H2b: The negative effect of non-aligned modularity and solution space freedom on organisational learning is weaker for less sophisticated suppliers than for more sophisticated suppliers.

### ***Sustainable innovation***

Sustainable innovation refers to transforming existing products and processes into more sustainable versions (Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016). Sustainable innovation is aimed at creating or improving products and processes to keep resource use and waste production within appropriate environmental limits (Foxon and Pearson 2008). This implies innovation in product and process technologies that are necessary for energy-saving, pollution prevention, waste recycling, green product designs or corporate environmental management (Chen, Lai, and Wen 2006). Reducing emissions, recycling and reducing the use of materials and resources are important aspects of sustainable process innovation. Choosing the least polluting materials, using the least amount of materials and resources and creating products that are easy to recycle, reuse and decompose are aspects of sustainable product innovation (Chen, Lai, and Wen 2006).

### ***Organisational learning and sustainable innovation***

We propose that TI firms can perform better at sustainable innovation through organisational learning. Innovation requires firms to actively build, adapt and apply knowledge through problem solving across functional barriers (Leonard-Barton 1995). These requirements also hold true for sustainable innovation, which requires firms to integrate ideas to protect the environment through innovation. If knowledge generated in one part of the firm can also be used elsewhere, innovativeness will improve (Knott 2003). Organisational learning is therefore considered to be directly related to TI firms’ ability to innovate, as it enables them to recognise the value of new information, assimilate it and apply it (Cohen and Levinthal 1990; Brown and Duguid 1991).

Thus far, we have proposed a (negative) positive relationship between (non-)aligning modularity and solution space freedom and organisational learning. Because organisational learning can cause TI firms to change their actions (Kane and Alavi 2007; Pavlou and El Sawy 2011), it qualifies as a key process between customisation and sustainable innovation. Existing research states that learning drives innovation (Cohen and Levinthal 1990) and that sustainable product

and process innovation are driven by the firm's dynamic processes (Ayuso, Rodríguez, and Ricart 2006; Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016). We therefore expect TI firms' sustainable innovation not to be directly affected by customisation, but rather, to be mediated by organisational learning. Formally:

H3: Organisational learning increases performance on (a) sustainable product innovation and (b) sustainable process innovation.

## Research methodology

### Sample

We prepared a survey instrument to collect the data required to test our hypotheses. Our final sampling frame was a sub-sample of Dutch business-to-business (B2B) firms which were subscribed to the newsletter of a high-profile Dutch industry magazine. We applied two selection criteria. First, we specifically stated in the cover letter of the survey that the questionnaire was aimed at firms active in the TI industry. Second, we explicitly stated that the survey required the respondents to have knowledge about modularity and customisation issues. The survey was sent to 395 industry professionals working in TI firms. A total of 255 respondents participated in the online survey. After we removed the invalid responses (mostly due to missing data that could not be reasonably imputed), we used the results of the remaining 166 respondents for further analyses, which is a response rate of 42%. The majority of the respondents were active in the machinery (45%) and electronic equipment (12%) industries. In addition, the majority of respondents worked at the departmental management level (30%) or at the higher management level (46%). We retrieved company names from 128 respondents and were able to control for potential differences or inflated results caused by respondents who work for the same company. In particular, we performed two robustness checks. First, we used a fixed effects model to control for unobserved differences between firm members. Second, we assessed inter-rater agreement (cf. Boyer and Verma 2000; all correlations  $> 0.7$ ) and merged questionnaires from respondents working for the same firm (leading to a sample size of  $n = 148$ ). Our findings remained robust to these alternative specifications.

To test for non-response bias, we followed the procedure suggested by Armstrong and Overton (1977). First, we collected Dutch census statistics on industry representation. The results of a  $t$ -test showed that the representation of respondents in our sample from different industries was not statistically different from the population characteristics ( $t = 1.36$ ,  $p > 0.10$ ). Second, we performed the extrapolation method, based on the assumption that subjects who respond less readily, incompletely or inaccurately are more like non-respondents. We found no significant differences between industry, function and tenure characteristics of groups of early respondents, late respondents and non-respondents, suggesting that non-response bias is not a serious threat. Third, we conducted a wave analysis according to the last respondent method using our final data-set. This method is recommended as it incorporates information about the trend in responses from early and later waves, yet stays within the range of the data (Armstrong and Overton 1977). Seventy-five per cent of the respondents in our final data-set participated in the first wave and twenty-five per cent in the second wave (i.e. after the first reminder). We then compared the responses of both groups to all the independent and dependent variables in our theoretical model. The results of the independent sample  $t$ -tests showed no significant differences between the groups (all  $p$ -values  $> 0.05$ ). Thus, we are confident that non-response bias is not a serious issue.

### Measures

The variables of interest in this study were measured using multi-item scales. The multi-item variables were based on an unweighted average of relevant items. For consistency, all items were measured using seven-point Likert scales. All survey items were based on or adapted from measures used in previous research and based on input from an expert panel of academics. Moreover, they were pretested on employees at TI firms who were knowledgeable about modularity, product development and operations issues. Only minor changes needed to be made following their remarks. Using our final sample, we conducted numerous analyses (described below) to verify that our measures were sound (see Gibson and Birkinshaw 2004 for similar practice).

The dependent variables, *sustainable product innovation* and *sustainable process innovation*, were both measured with four items obtained from previous research by Albort-Morant, Leal-Millán, and Cepeda-Carrión (2016) and Chen, Lai, and Wen (2006). The *degree of modularity* was measured with five items derived from Ghosh, Dutta, and Stremer-sch (2006) and Worren, Moore, and Cardona (2002). *Solution space freedom* was measured with five items adapted from previous work by Steiner (2014) and Wellige and Kleer (2015). *Organisational learning* was measured with five items obtained from previous work by Pavlou and El Sawy (2011). *Supplier sophistication* was measured with eight

items based on scales adapted from previous work on supplier quality control, delivery performance, and innovativeness (Krause, Pagell, and Curkovic 2001; Primo and Amundson 2002; Azadegan and Dooley 2010). Internal reliability of all constructs is high ( $\alpha$ 's > 0.8). The complete set of measurement items for our constructs, including the item loadings and reliability, is provided in Table 1.

As firm size is known to affect innovative performance and learning (Cohen and Levin 1989; Knott 2003), we controlled for this variable in our analyses. Firm size was measured as a dummy variable, which indicated whether the focal firm was small, medium or large.

Table 1. Measurement items, item loadings and reliability.

Scale	Items	Loading path	Cronbach's $\alpha$
Sustainable product innovation	We choose materials that produce the least amount of pollution for our solution development or design	0.89	0.89
	We choose materials that consume the least amount of energy and resources for our solution development or design	0.85	
	We use the fewest amount of materials to comprise the solution during development or design	0.69	
	We deliberate whether the solution is easy to recycle, reuse and decompose before conducting development or design	0.82	
Sustainable process innovation	We effectively reduce the emission of hazardous substances or waste in the manufacturing processes	0.86	0.88
	We recycle waste and emissions, and allow them to be treated and re-used in manufacturing processes	0.80	
	We reduce the consumption of water, electricity, coal or oil	0.80	
Modularity	We reduce the use of raw materials in the manufacturing process	0.78	0.85
	Our solutions have been decomposed into separate modules	0.72	
	The configuration of our solutions is based on standard interfaces	0.83	
	The composition of our solutions is perfectly modular	0.83	
	The composition of our solutions can be chosen without taking into account other aspects (e.g. components, design, standards) of the product	0.70	
Solution space freedom	Certain aspects of our solution configuration can be easily replaced with similar configurations from another manufacturer without raising compatibility issues (D)	0.50	0.80
	We define an initial set of functional attributes that meets the heterogeneous requirements of a broad group of customers (R)	0.82	
	We develop an initial set of functional components that addresses a large numbers of different customer requirements (R)	0.86	
	We have a 'choice menu' of features or components that customers can choose from in order to create solutions (D)	0.64	
	We restrict customer choices to options that are already present in the system (R)	0.56	
	We have a predefined all possible changes of designs that are offered to customers (R)	0.53	
Organisational learning	We have effective routines to identify, value and import new information and knowledge	0.84	0.91
	We have adequate routines to assimilate new information and knowledge	0.85	
	We are effective in transforming existing information into new knowledge	0.88	
	We are effective in utilising knowledge into new solutions	0.77	
	We are effective in developing new knowledge that has the potential to influence development	0.77	
Supplier sophistication	Our suppliers are proactive in approaching us with innovations	0.71	0.84
	Our suppliers are very capable of collaborating and providing reliable input	0.83	
	Our suppliers have well-developed project management capabilities	0.70	
	Our suppliers are able to conform to our specifications	0.68	
	The level of technological capabilities of our suppliers is low (R) (D)	0.45	
	Our suppliers consistently deliver products on promised due dates (D)	0.54	
	Our suppliers are willing to share key technological information	0.78	
	Our suppliers have quality and process certifications that are relevant in our industry (D)	0.58	

Notes: Reverse-coded items are indicated by (R), deleted items are indicated by (D).

### Validation

We assessed external validity by presenting our findings during a group discussion with 66 managers from TI industries. These managers confirmed our interpretations, which strengthened our beliefs that the findings are generalisable. Furthermore, 53% of these managers stated that their firm combined high degrees of modularity with high degrees of solution space freedom, while 14% combined high degrees of modularity with low degrees of solution space freedom. Thus, we are confident that our proposed alternative conceptualisation of customisation is prevalent in TI firms.

We first conducted a principal component analysis (PCA) to validate our assumption that modularity and solution space freedom are both separate dimensions of customisation. After removing item 3 of the solution space freedom scale, which had a cross-loading above 0.45 and correlated the lowest with the other items in the scale, we generated two components with PCA, both with Cronbach's  $\alpha$  above 0.8. We next assessed convergent and discriminant validity and found that correlations between factors did not exceed 0.7, all average variances extracted (AVE) exceeded 0.5, and all maximum shared variances (MSV) < AVE (Bagozzi and Yi 1988; Henseler, Ringle, and Sarstedt 2015) (see Table 2). To assess model fit, we conducted a confirmatory factor analysis (CFA) to simultaneously validate the measures of all the variables used in this study. The results of the CFA are presented in Table 2. The items loaded significantly on their respective constructs. To improve model fit we decided to only include items with loadings above 0.5 or delete items to increase the scale's threshold to 0.7. The item loadings and the overall model fit results suggest acceptable unidimensionality and convergent validity for the measures (Bollen 1989; Bagozzi, Yi, and Phillips 1991; Hoskisson et al. 1993). The results of the final model show an acceptable fit ( $\chi^2/df$ ) = 1.66; Comparative Fit Index (CFI) = 0.93; Tucker–Lewis Index (TLI) = 0.92; Root Mean Square Error of Approximation (RMSEA) = 0.06, PCLOSE = 0.02, 90% CI = [0.05, 0.07]).

We tested model fit again by loading all items of sustainable product innovation and sustainable process innovation onto one variable (cf. Albort-Morant, Leal-Millán, and Cepeda-Carrión 2016). As a model with a composite construct for sustainable innovation has a worse model fit ( $\chi^2/df$ ) = 1.99; CFI = 0.89; TLI = 0.88; RMSEA = 0.08; PCLOSE = 0.00), we decided to continue with our initial model that includes sustainable product innovation and sustainable process innovation as separate constructs (cf. Chen, Lai, and Wen 2006).

### Common method variance

We followed several procedural steps suggested by Podsakoff et al. (2003) in order to avoid common method bias. We separated the proximity and methodology of the measurements and used a cover story to ensure anonymity and reduce evaluation apprehension. However, since the data-set contained responses from single respondents across multiple firms, common method variance needed to be checked to ensure that there were no major problems caused by response bias. Following the steps suggested by Podsakoff et al. (2003, 898), we controlled for an unmeasured latent method factor. We compared the CFA of this model to our theoretical model and found that the model fit worsened (BIC = 936.69) and the common latent factor accounted for less than 1% of the total variance. Furthermore, we compared the factor loadings of our items on their theoretical constructs and found that none significantly decreased or increased. Common method variance is most likely a problem when biased responses inflate or deflate bivariate linear relationships (Podsakoff, MacKenzie, and Podsakoff 2012). While biased responses inflate linear effects (Podsakoff, MacKenzie, and Podsakoff 2012), they cannot inflate quadratic and interaction effects (Siemens, Roth, and Oliveira 2010). As we mainly use the polynomial regression (and interaction) terms to test the majority of our hypotheses, common method bias might be less of an issue. Altogether, we do not consider common method variance to be an issue for this study.

Table 2. Convergent and discriminant validity.

Construct	CR	AVE	MSV	1	2	3	4	5	6
1. Sustainable product innovation	0.89	0.67	0.64	<b>0.82</b>					
2. Sustainable process innovation	0.88	0.66	0.64	0.80	<b>0.81</b>				
3. Modularity	0.85	0.60	0.39	0.39	0.39	<b>0.77</b>			
4. Solution space freedom	0.80	0.51	0.39	−0.27	−0.16	−0.62	<b>0.71</b>		
5. Organisational learning	0.90	0.65	0.25	0.50	0.47	0.45	−0.25	<b>0.81</b>	
6. Supplier sophistication	0.86	0.55	0.18	0.25	0.36	0.29	−0.12	0.42	<b>0.74</b>

Notes: All CR > 0.7; all AVE > 0.5; all MSV < AVE. Bold values on the diagonal represent the square root of the AVE, none are lower than their correlations with another factor. These results indicate that there are no validity concerns.

### Analytical approach

A polynomial response surface modelling technique is recommended as an effective analytical approach to assess how the combination of two predictor variables that share a conceptual domain relates to an outcome (Edwards and Parry 1993; Edwards and Cable 2009; Shanock et al. 2010; Auh et al. 2016). Polynomial regression can be used instead of moderated regression, as it provides much more information about combinations of variables compared to traditional moderated regression techniques (Shanock et al. 2010). Traditional difference scores confound the effects of each of the component measures on the outcome and are thus unable to show the extent to which each of the components contributes to the outcome variable. Difference scores also do not allow us to determine whether or not components should exceed or align with each other to achieve the desired outcome, whereas polynomial regression allows us to retain the independent effect of each component measure and to examine the extent to which each component contributes to variance in the outcome. Furthermore, our three-dimensional model offers more valuable information than two-dimensional models, which aids in the interpretation of our results. For more detailed and sophisticated discussions, and to fully understand the differences between using polynomial regression and difference scores, interested readers might consult Shanock et al. (2010), Edwards (1994, 2002), Edwards and Parry (1993), and Edwards and Cable (2009).

Because the degree of modularity and solution space freedom share the same conceptual domain, i.e. customisation, we can apply the polynomial modelling technique to test our hypotheses. We also meet the other key assumptions of this method, since our predictor variables are measured on the same numeric scale in order to determine the degree of correspondence (Edwards 2002; Shanock et al. 2010). Before conducting the polynomial regression analyses, we should determine the base rate of discrepancies in our sample (Shanock et al. 2010). We therefore standardised the scores of predictor constructs and compared the percentages of participants with standardised scores on one predictor variable that are half a standard deviation above or below the score on the other variable. We computed the difference in scores on modularity more than half a standard deviation from solution space freedom and found that over 55% of our sample has values that meet this criterion. We therefore conclude that it makes practical sense to explore how discrepancies between these dimensions of customisation relate to organisational learning.

We estimated the dependent variable by entering five polynomial terms into the equation, specifically, modularity (M), solution space freedom (S) and the three higher order effects (i.e.  $M^2$ ,  $S^2$  and  $MS$ ) that were created as product terms of M and S after scale-centring (cf. Edwards and Cable 2009). The estimated coefficients that are related to how each term individually affects organisational learning were not directly employed to test any hypothesis, but were used to compute the slope and curvature along the (non-)alignment lines (Edwards and Parry 1993). Since the  $R^2$  of learning was significantly different from zero (see Table 3), we could then evaluate the four surface tests rather than examine the regression coefficients as in common regression analysis (Edwards 2002; Shanock et al. 2010). Conform Shanock et al. (2010), we computed the slopes and curvatures along the alignment ( $M = S$ ) and non-alignment ( $M = -S$ ) lines as alignment slope ( $M + S$ ) and curvature ( $M^2 + MS + S^2$ ) and non-alignment slope ( $M - S$ ) and curvature ( $M^2 - MS + S^2$ ).

### Results

Table 3 reports the estimated standardised coefficients. Model 1 (i.e. the baseline model) indicates that the degree of modularity is positively and significantly related to organisational learning (0.38,  $p < 0.01$ ). We used the estimated coefficient for each polynomial term to compute the slope and curvature along the (non-)alignment lines, which appear in Table 4. Along the non-alignment line ( $M = -S$ ), the slope is positive and significant (0.33,  $p < 0.01$ ), while the curvature is negative and significant ( $-0.12$ ,  $p < 0.05$ ). The inverted U-shape suggests that customisation through both high degrees of modularity with low degrees of solution space freedom and low degrees of modularity with high degrees of solution space freedom results in lower levels of organisational learning. Moving along the non-alignment curvature in Figure 3, we see that the degree of non-alignment is more important than the direction of non-alignment. To the left and right of Figure 3, we see that organisational learning decreases as the balance of a customisation approach changes in favour of either higher degrees of modularity or higher degrees of solution space freedom.

Along the alignment line ( $M = S$ ), only the slope is positive and significant (0.27,  $p < 0.05$ ), while the curvature is not (see Table 4). Moving along the alignment slope in Figure 3, we see that the level of organisational learning is lower when both the degree of modularity and solution space freedom are low. This level increases when these customisation dimensions are both equally present and high. Thus, these results indicate that the slope of the surface of the alignment line is positive and linear and that organisational learning is higher when modularity and solution space freedom are both high than when they are both low (cf. Edwards and Parry 1993, 1597). Overall, these findings lend support for H1a and H1b, such that (non-)alignment of modularity and solution space freedom (negatively) positively affects organisational learning.



Table 3. Model results.

Direct (polynomial) effects		Model 1	Model 2	Model 3
Modularity (M)	Organisational learning	0.38**	0.38**	0.37**
Solution space freedom (S)	Organisational learning	-0.03	-0.03	-0.02
M <sup>2</sup>	Organisational learning	-0.11	-0.11	0.02
M × S	Organisational learning	0.18	0.18	0.21
S <sup>2</sup>	Organisational learning	0.06	0.06	-0.00
M	Sustainable product innovation		0.16	
S	Sustainable product innovation		-0.10	
M <sup>2</sup>	Sustainable product innovation		0.18*	
M × S	Sustainable product innovation		-0.02	
S <sup>2</sup>	Sustainable product innovation		-0.12	
M	Sustainable process innovation		0.16	
S	Sustainable process innovation		0.01	
M <sup>2</sup>	Sustainable process innovation		0.06	
M × S	Sustainable process innovation		-0.18	
S <sup>2</sup>	Sustainable process innovation		-0.11	
Organisational learning	Sustainable product innovation	0.44**	0.39**	0.44**
Organisational learning	Sustainable process innovation	0.45**	0.42**	0.45**
Supplier sophistication	Organisational learning			0.42**
M × Supplier sophistication	Organisational learning			-0.16
S × Supplier sophistication	Organisational learning			-0.06
M <sup>2</sup> × Supplier sophistication	Organisational learning			-0.17
M × S × Supplier sophistication	Organisational learning			-0.11
S <sup>2</sup> × Supplier sophistication	Organisational learning			-0.05
Firm size: Medium	Organisational learning	-0.16	-0.16*	-0.17*
Firm size: Large	Organisational learning	-0.10	-0.10	-0.10
Firm size: Medium	Sustainable product innovation	0.05	0.08	0.05
Firm size: Large	Sustainable product innovation	0.05	0.03	0.05
Firm size: Medium	Sustainable process innovation	0.15	0.18*	0.15
Firm size: Large	Sustainable process innovation	0.24**	0.25**	0.24**
AIC		1526.97	1519.10	1511.00
RMSEA		0.10	0.00	0.07
CFI		0.91	1.00	0.91
TLI		0.78	1.00	0.82
R <sup>2</sup> Organisational learning		0.22**	0.22**	0.34**
R <sup>2</sup> Sustainable product innovation		0.19**	0.28**	0.19**
R <sup>2</sup> Sustainable process innovation		0.23**	0.29**	0.23**

Notes: We report the standardised coefficients estimated from the main and interaction effects models.

\* $p < 0.05$  (2-tailed test);

\*\* $p < 0.01$  (2-tailed test).

Table 4. Slope and curvature for (non-)alignment lines.

	Model 1	Model 3	
	Polynomial effects	Low supplier sophistication	High supplier sophistication
<i>Alignment (M = S)</i>			
Slope (M + S)	0.27*	0.43	0.13
Curvature (M <sup>2</sup> + MS + S <sup>2</sup> )	0.08	0.24	0.01
<i>Non-alignment (M = -S)</i>			
Slope (M - S)	0.33**	0.38*	0.24**
Curvature (M <sup>2</sup> - MS + S <sup>2</sup> )	-0.12*	-0.09	-0.13**

\* $p < 0.05$  (2-tailed test);

\*\* $p < 0.01$  (2-tailed test).

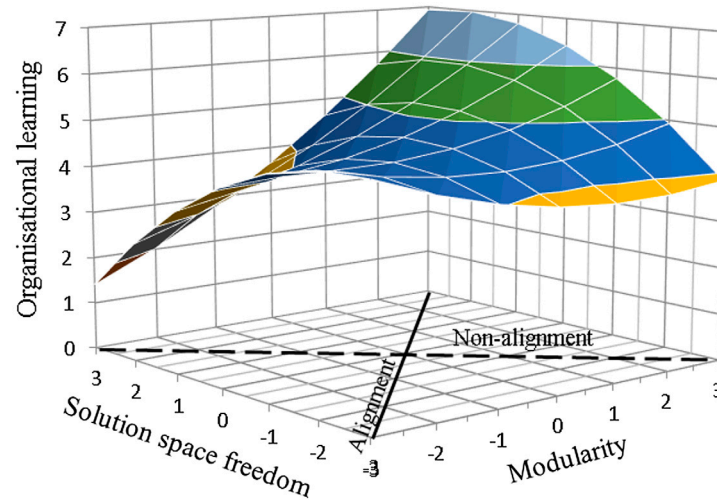


Figure 3. Organisational learning as a function of modularity and solution space freedom.

### Moderation

To test the interaction hypotheses (H2a–b), we followed the approach suggested by Aiken, West, and Reno (1991) and tested the polynomial moderation hypotheses by adding supplier sophistication and the interaction with each polynomial term to the model. After estimating the interaction effects model, we computed two equations: one for firms with highly sophisticated suppliers (where we substituted values one standard deviation ( $\delta = 1.07$ ) above the mean) and the other for less sophisticated suppliers (where we substituted values one standard deviation ( $\delta = 1.07$ ) below the mean). We then tested the hypotheses by computing the slope and curvature along the (non-)alignment lines. Table 3 indicates that Model 3 results in smaller Akaike information criteria (AIC) values than Models 1 and 2, suggesting that the interaction effects model is appropriate. We used the estimated coefficients from Model 3 to compute the slopes and curvatures at high and low levels of supplier sophistication (cf. Aiken, West, and Reno 1991). As Table 4 shows, for lower levels of supplier sophistication, only the slope along the non-alignment line is positive and significant ( $0.38, p < 0.05$ ), whereas for higher levels of supplier sophistication, both the slope ( $0.24, p < 0.01$ ) and the curvature ( $-0.13, p < 0.01$ ) of the non-alignment line are significant. In both cases, the slope of the alignment line is no longer significant. We therefore conclude that, when suppliers are less sophisticated, both the positive effect of alignment and the negative effect of non-alignment on learning are decreased. In Figure 4, we show how the non-alignment curvature is affected for both low and high levels of supplier sophistication. For less sophisticated suppliers, the direction of non-alignment differentially influences organisational learning, depending on either the degree of modularity or the degree of solution space freedom. When the degree of modularity is higher than the degree of solution space freedom, organisational learning will be less affected compared to when the degree of solution space freedom is higher than the degree of modularity. This different

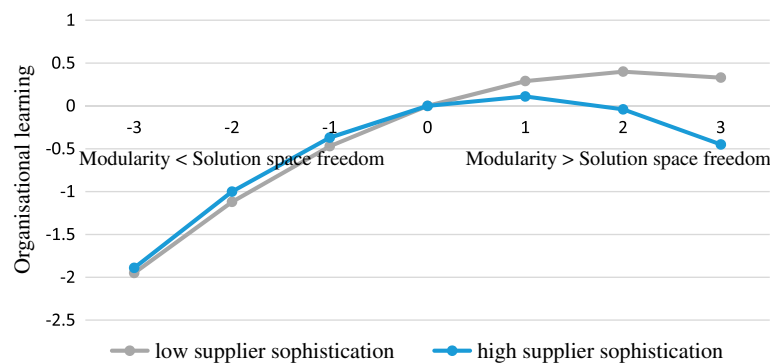


Figure 4. The effect of non-aligned modularity and solution space freedom on organisational learning for low and high supplier sophistication.

effect is represented by a significant positive slope of the non-alignment line for less sophisticated suppliers. As can be seen in Figure 4, organisational learning seems to increase as the degree of modularity (but not the degree of solution space freedom) increases to 2, but this effect levels off again as the degree of modularity increases further. In contrast, the non-alignment curvature remains negative for firms working with highly sophisticated suppliers, suggesting that the highest levels of organisational learning are achieved through balancing moderate levels of modularity and solution space freedom. Overall, these findings provide support for H2b, but not for H2a.

### Mediation

To test the mediation hypotheses (H3a-b), we employed the block variable approach (cf. Edwards and Cable 2009). We multiplied the polynomial regression coefficients from Model 1 by the raw data to compute the block variable as a weighted composite score, which is  $b_{C1}M + b_{C2}S + b_{C3}M^2 + b_{C4}MS + b_{C5}S^2$ . In the following mediation analysis, the block variable represents customisation and replaces the polynomial terms (Edwards and Cable 2009). We used a bootstrapping technique (5000 samples) to compute the bias-corrected confidence intervals (CIs) of 95% and test the significance of the indirect effects. Table 5 presents the results of this analysis.

The block variable representing customisation (composed of modularity and solution space freedom) is positively related to organisational learning (0.42,  $p < 0.01$ ). In addition, organisational learning is positively related to sustainable product innovation (0.42,  $p < 0.01$ ) and sustainable process innovation (0.45,  $p < 0.01$ ), and the effects of customisation on sustainable product and process innovation are not significant when organisational learning is taken into account (i.e. full mediation). Bias-corrected bootstrapped confidence intervals of the indirect effects of customisation on sustainable product innovation (0.17, 95% CI = [0.09, 0.28]) and sustainable process innovation (0.19, 95% CI = [0.10, 0.31]) exclude zero. Overall, these findings lend support for H3a and H3b such that organisational learning fully mediates the effects of customisation on sustainable product and process innovation.

### Discussion

TI firms are urged to prioritise both sustainability (Flores et al. 2008; Figge and Hahn 2012) and customisation (Davie, Stephenson, and De Uster 2010). However, pursuing both is difficult because sustainable innovation requires changing designs, development and production processes (Flores et al. 2008), while customisation challenges traditional operational boundaries (Åhlström and Westbrook 1999). In this paper, we argue that TI firms should not consider customisation and sustainable innovation as a trade-off. Rather, TI firms can increase sustainable innovation through customisation. In particular, we argue that customisation can be conceptualised along two dimensions, i.e. the degree of modularity and the degree of solution space freedom, and we show that customisation can foster sustainable product and process innovation through organisational learning. Additionally, we show that supplier sophistication moderates the relationship between customisation and organisational learning.

Table 5. (In)Direct effects relating customisation to organisational learning and sustainable innovation.

	Sustainable product innovation	Sustainable process innovation	Organisational learning
<i>Direct effects</i>			
Organisational learning	0.42**	0.45**	
Customisation	0.06	0.01	0.42**
Firm size: Medium	0.05	0.15	-0.17*
Firm size: Large	0.04	0.24*	-0.10
<i>Indirect effects</i>			
Customisation	0.17**	0.19**	
$R^2$	0.23**	0.20**	0.21**

Notes: The term 'Customisation' refers to the block variable constructed from the five polynomial terms for TI firms' customisation approach (i.e. degree of modularity, solution space freedom, their squares and their product). We report the standardised coefficients estimated from the model with the block variable. Bias-corrected bootstrapped confidence intervals of the indirect effects of customisation on sustainable product innovation (0.17, 95% CI = [0.09, 0.28]) and sustainable process innovation (0.19, 95% CI = [0.10, 0.31]) exclude zero.

\* $p < 0.05$  (2-tailed test);

\*\* $p < 0.01$  (2-tailed test).

### Implications

Our findings have implications for both academics and practitioners. First, from an academic perspective, we further advance our understanding of customisation, which has far-reaching implications for operations management (Åhlström and Westbrook 1999). In response to the pressure on TI firms to offer complex solutions (Lingqvist, Plotkin, and Stanley 2015), several papers have been published on implementing and excelling at mass customisation (e.g. Duray et al. 2000; Hvam 2006; Davies, Brady, and Hobday 2007; Wang et al. 2014), on the importance of using modularity to achieve manufacturing flexibility (e.g. Ulrich 1995; Duray et al. 2000; Baldwin and Henkel 2015), or on how the solution space represents design flexibility (e.g. Salvador, De Holan, and Piller 2009; Lyons et al. 2013). An assumption underlying these related literature streams is that the effects of modularity and solution space freedom are independent. This study proposes a more nuanced perspective by combining both of these critical, interrelated identifiers of customisation and compares the effects of varying combinations. This complementary view broadens the current debate on customisation. Our results corroborate the proposed nuance to customisation as we find that varying degrees of modularity and solution space freedom result in various learning rates within TI firms. Therefore, this study contributes to the literature on customisation and the role of modularity (Salvador, De Holan, and Piller 2009; Sanchez and Collins 2001; Steiner 2014; Wang et al. 2017) by offering a more hybrid perspective and by showing that the effects of modularity should be considered jointly with the freedom to accommodate customer-specific designs.

Second, we contribute to the existing literature on organisational learning (e.g. Schilling et al. 2003; Narayanan, Balasubramanian, and Swaminathan 2009; Staats and Gino 2012) by showing that organisational learning explains how TI firms are able to arrive at win-win situations in which they simultaneously pursue customer-specific manufacturing and sustainable innovation. With this finding, we contribute to literature on (organisational) learning that has previously suggested that balancing both knowledge specialisation (arising from modularity) and knowledge variety (arising from free solution spaces) is needed to foster learning (e.g. Schilling et al. 2003; Narayanan, Balasubramanian, and Swaminathan 2009; Staats and Gino 2012).

In addition, we add to previous research stating that architectural decisions affect TI firms' knowledge processing mechanisms (Brusoni and Prencipe 2001; Brusoni et al. 2007), as the results of our polynomial regression analysis show that balanced and equally present customisation dimensions indeed affect organisational learning. To be specific, establishing either knowledge specialisation or variety in isolation through either high degrees of modularity or solution space freedom leads to suboptimal organisational learning. In contrast, an ambidextrous approach of aligning high degrees of modularity to high degrees of solution space freedom increases organisational learning. We thus empirically confirm that highly modular architectures may negatively affect organisational learning (Robertson, Casali, and Jacobson 2012) but alignment to high degrees of solution space freedom allows TI firms to achieve learning benefits (Schilling et al. 2003).

Further, our mediation results show that organisational learning is the mechanism that explains how modularity and solution space freedom affect sustainable innovation. Some authors have argued that modularity affects sustainability (Davies, Brady, and Hobday 2007) because it allows firms to upgrade solutions to increase their life cycle (Brusoni and Prencipe 2001). Others have suggested that modularity may detract from achieving sustainability goals (Medini, Da Cunha, and Bernard 2015). Researchers have also suggested that modularity may directly improve product innovativeness, albeit with diminishing returns (Lau, Yam, and Tang 2011), but the same researchers have argued that the effects of modularity on product performance are mediated by learning (Lau, Yam, and Tang 2007). Our results somewhat reconcile these conflicting findings. To be specific, our results support early work suggesting that modularity affects learning (Langlois and Robertson 1992) and corroborate research stating that the performance effects of modularity are mediated by internal processes (e.g. Worren, Moore, and Cardona 2002; Jacobs, Vickery, and Droge 2007). To conclude, organisational learning enables TI firms to change their actions with respect to sustainable innovation through the acquisition, distribution and interpretation of knowledge and insights gained via customisation.

Third, our model builds on knowledge theory to account for the moderating role of supplier sophistication. Solving customers' business problems requires different types of knowledge and capabilities, which are often distributed among the firm's partners (Brusoni and Prencipe 2013). Contrary to our expectations, the positive effect of aligning modularity and solution space freedom on organisational learning disappears for TI firms working with highly sophisticated suppliers. Rather, moderate degrees of modularity and solution space freedom, and thus knowledge specialisation and variety, may increase organisational learning when the supplier base is highly sophisticated. A possible explanation could lie in the learning mechanisms that are at play. Because the costs of understanding (or developing) knowledge within the firm are greater than those of obtaining knowledge from suppliers (Williamson 1985), TI firms might not want to acquire all relevant knowledge themselves and instead delegate knowledge to suppliers (Robertson, Casali, and Jacobson 2012). Therefore, under the condition that TI firms are able to gain knowledge from sophisticated suppliers, high levels of knowledge specialisation or variety may no longer be necessary.

The mitigated learning effect of non-alignment when suppliers are less sophisticated suggests that customisation with higher degrees of modularity (and slightly lower degrees of solution space freedom) enhances organisational learning. These findings might be explained in light of the mirroring hypothesis, which suggests that there can be two opposite knowledge sharing mechanisms at play when firms leverage modularity (Cabigiosu and Camuffo 2012; Furlan, Cabigiosu, and Camuffo 2014; Colfer and Baldwin 2016). Our findings suggest that higher degrees of modularity may imply either less knowledge sharing when suppliers are more sophisticated (the ‘trade-off’ hypothesis) or more knowledge sharing when suppliers are less sophisticated (the ‘complementarity’ hypothesis). These findings contribute to previous research by suggesting that both knowledge-intensive and routine-intensive suppliers may contribute to organisational learning in different ways (Azadegan 2011).

From a practitioner’s viewpoint, our research presents actionable guidance. In particular, this study shows that customisation can be a suitable strategy for TI firms to exploit ‘win-win’ situations that reconcile environmental protection and customer demands. Instead of increasing the degree of modularity and decreasing the degree of solution space freedom, as is common with mass customisation, our findings suggest that managers of TI firms looking to increase levels of organisational learning and sustainable innovation should balance both highly modular designs and unconstrained solution spaces. Moreover, managers might be interested to consider the sophistication of their supplier base before deciding on their customisation approach, as supplier sophistication influences the focal firm’s learning processes. Alternatively, we may expect managers to decide to cooperate more or less intensely with their suppliers, depending on the learning effects they want to achieve. Overall, our findings show that sustainability objectives should not necessarily be sacrificed when adopting customisation. Rather, customised manufacturing environments may contribute to sustainable innovation when managers consider alternatives to well-known approaches like mass customisation.

### ***Limitations and future research directions***

This study has a number of limitations, some of which provide interesting avenues for future research. First, we used a survey to assess the relationships between customisation, organisational learning and sustainable innovation. The results of this survey indicated that aligning high degrees of modularity to high degrees of solution space freedom results in the highest organisational learning rate. Since a survey only offers a snapshot in time, future research might consider developing a dynamic model to assess whether firms switching to such a customisation approach indeed perform better, both on organisational learning as well as on sustainable innovation.

Second, we controlled for an unmeasured latent method factor to assess common method variance. While this method is recommended when researchers have not incorporated marker variables (Podsakoff et al. 2003), for the sake of prudence we suggest that future research adopt marker variables in order to capture possible types of common method variance (e.g. social desirability, positive or negative affectivity).

Third, while the focus of our study was on establishing a link between customisation and organisational learning, our findings provide limited insights on organisational learning and how it is affected by customisation tasks embedded in modularity and solution space freedom. For example, the results suggest that aligning lower degrees of modularity to less solution space freedom results in higher organisational learning compared to non-aligning higher degrees of modularity to lower degrees of solution space freedom (i.e. mass customisation). This result contradicts research that showed that mass customisation had a more positive effect on organisational learning than standardised approaches like mass production (Kotha 1995). This contradictory result might be explained by the fact that TI firms with standardised customisation processes can benefit from integral designs that enhance knowledge sharing and interactive learning (Mikkola 2003). Future research might consider which firm capabilities explain the varying performance outcomes of the different customisation approaches. Additionally, other value chain characteristics (e.g. customer and supplier characteristics) affecting firm performance should be taken into account.

Fourth, we did not find that high supplier sophistication affects the relationship between aligning modularity and solution space freedom and organisational learning, which indicates that other mechanisms (e.g. the degree of outsourcing, relationship quality) might be at play to explain how innovative, knowledge-intensive tasks on both the firm and supplier side may jointly affect organisational learning. Future research might explore these mechanisms and account for other characteristics of partners in the value chain.

### **Disclosure statement**

No potential conflict of interest was reported by the authors.



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