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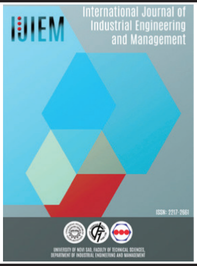

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Original research article

When Modularity Meets Mind: Product Innovation through a Behavioral Lens

M. A. Tiruneh[a,*] 0000-0003-1611-1293, N. Suzic[a] 0000-0003-0755-9774, F. Turner[b] 0000-0002-1461-1959

[a] *Department of Industrial Engineering, University of Trento, Trento, Italy;*
[b] *School of Business, Ithaca College, Ithaca, New York, USA*

ABSTRACT

Modular Product Design (MPD) is a promising strategy for managing complexity in product development. However, researchers disagree on the MPD's impact on product innovation. Some researchers argue that MPD facilitates innovation, while others contend that it hinders it. This conceptual paper develops a framework that aims to reconcile these contradictory findings from the literature. Thus, we build on the current understanding in the field of MPD, identifying two literature streams that have different views on the impact of MPD on product innovation. To reconcile these views, we adopt an interdisciplinary approach that integrates bodies of research on MPD and innovation with insights from behavioral science. Finally, after analyzing the relevant literature on MPD and behavioral science, we conceptualize a framework that proposes that designers' cognitive behavior moderates MPD's impact on product innovation, explaining this long-standing debate in the field. In this way, the proposed conceptual framework reconciles the conflicting arguments on MPD's impact on product innovations and potentially opens a new field of study, shedding light on this behavioral blind spot of existing research.

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*Corresponding author:
Muluken Abebe Tiruneh
mulukenabebe.tiruneh@unitn.it

1. Introduction

Product innovation, both incremental and radical [1], is inherently uncertain due to the increased need for product variety [2], [3], advancement of technology, and its design complexity [4]. To manage these uncertainties, a Modular Product Design (MPD) approach plays a crucial role [4]-[7]. The concept of MPD is rooted in product modularization, which means that "products of one product family are partitioned into highly independent (or loosely coupled) and preferably function-specific product modules" [8] (definition based on Sanchez and Mahoney [9], Duray et al. [10], Salvador, Forza, and Rungtusanatham [11], and Hsuan Mikkola and Skjøtt-Larsen [12]). Following Ulrich's [3] seminal paper on product architecture, numerous researchers added to the findings on modular products. These studies discussed the development of modular products [7], definitions and benefits of modular products [6], [13], tools and methods for implementing modularity [6], [14]-[16], and the role of product modularization, particularly in implementing mass customization [8], [12], [17]-[19].

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Research has linked product modularization with product design, that is, MPD as noted above [5], [20] and connected it to innovation, with conflicting results: some researchers indicate that modularization facilitates product innovation [1], [15], [21], [22], while others assert that it hinders product innovation [4]. Innovation is widely used in both academic and industrial sectors and is defined differently depending on the perspectives adopted [23], [24], [25]. Broadly, innovation refers to the generation, acceptance, and implementation of new ideas that create value [23], [26]. However, this broad definition does not fully capture the characteristics of innovation within MPD, which warrants a contextual definition. In this regard, we define innovation as the successful realization and implementation of new ideas in an MPD, with rational cognitive thinking serving as a basic component in the design process that transforms an existing product into a new version. Thus, novel ideas that transform the MPD to innovative product do not occur by themselves; rather, they are the result of designers' decision-making effort, which is driven by their *cognitive behavior* [27]-[29]. Building on the traditional economic theory, *homo economicus,* Tversky and Kahneman [30], [31] introduced the concept that real-world decision-making (i.e., humans) deviates from completely rational models (i.e., rational agents) assumed in classical economics. They argue that this is due to heuristics or mental shortcuts and cognitive biases, which are often driven by intuitive thinking (System 1). Thaler [32] supported this work and further formalized it by introducing the term "econ" to describe a perfectly rational agent assumed in the standard economic models, contrasting them with humans, who make systematic deviations from rational decision-making due to cognitive biases and heuristics-driven thinking. Applying this reasoning to MPD is interesting, as designers are not *econs* but are, as all humans, often influenced by heuristics. Notably, the effect of designers' cognitive behavior on MPD's innovation effects remains out of the existing literature's focus. Thus, there is a gap in the research that needs further investigation in order to better understand how cognitive behavior influences designers' decisions in MPD, leading to innovative or less innovative products.

The present study aims to make initial steps in filling this research gap by exploring how designers' cognitive behavior influences MPD and innovation. Specifically, we examine the effect of heuristics in design decisions during MPD using a conceptual framework developed from a critical review of extant literature and analytical reasoning, leading to a conclusion that could potentially open a new field of research. Accordingly, we set the objective of the present research as follows: *To conceptualize a framework that will reconcile the opposing views on the impact of MPD on product innovativeness*. Our research begins with an examination of the available MPD literature, which, as already noted, provides contradictory views regarding its impact on product innovativeness. Therefore, we argue that product innovation is impacted not only by the MPD concept but also by the designers' reasoning, which is the source of cognitive biases [30], [33].

The remainder of the paper is organized as follows: Section 2 presents the theoretical background on MPD and product innovation. Section 3 outlines the research methodology. Section 4 discusses the conceptual framework that has a goal to reconcile the two opposing views of MPD on product innovation. Finally, Section 5 provides the conclusion, study implications, and proposes future research directions.

2. Theoretical background

2.1 Modular Product Design

Modular products consist of modules [6], [7], which are composed of components [7] that can be independently changed to fulfill various functions [7], [15]. Building on the notion that modular products are the result of interchangeable modules, Bonvoisin et al. [5] defined MPD as an "*activity of designing a product that is made up of modules*." Although this study does not provide a detailed step-by-step explanation of the MPD activities, it supports the design process of how the desired modular requirements are mapped into their functional space that supports the MPD process [20]. This concept was initially referred to as modular product architecture by Ulrich [3], which was later accepted in the research literature [7], [34].

MPD offers important advantages in the product development process, including design complexity reduction, facilitating product updates as new technologies emerge [6], [35] , and increasing product variety that the company can offer to its customers [7], [12], [16], [36]. In fact, these advantages have been widely addressed in the mass customization literature [17], [37]-[40]. Moreover, studies have examined the effect of MPD on innovation, addressing both positive and negative impacts [22], [27], [41].

2.2 Modular Product Design and Product Innovation

Today, manufacturing companies are faced with global competition, shortened product life cycles, and clients asking for a high product variety. This dynamism forces companies to offer a broad array of innovative products to maintain their competitive advantages [42], [43]. However, innovative product development is inherently uncertain due to technological advancement and design complexity [4], existence of many different parts in a product [44] , and product architecture [3], [45]. To manage these uncertainties and maintain the competitive advantages by offering a range of new products, MPD approach has become a viable solution [6], [7], [46]. On the one hand, by designing interchangeable modules, designers can rapidly adapt to changing customer needs through updating planned product changes, integrating new technologies [47], and developing new product styles [48]. Thus, MPD maintains the company's competitive advantage and enables it to offer continuously innovative modular products. For example, the asymmetrical dependencies of modular interfaces within the MPD system necessitate significant design modifications [49], which require designers' cognitive effort to integrate modules effectively and ensure proper functionality. This process compels designers to explore novel solutions in MPD, ultimately facilitating innovation [49], [50]. On the other hand, some researchers argue that MPD impedes innovation. This research stream supports the product innovation-hindering position with different arguments. For example, some researchers argue that the fact that MPD bases its designs on the existing product architecture [22] is the reason for obstructing innovation. Others find reasons in the designers' tendency to focus on specific designed modules [35]. Finally, some researchers conclude that designers recalling previously designed experiences [51] could be the reason for less innovative results of MPD.

We proceed to present an in-depth analysis and conceptualization of a framework that examines the contradictory views on MPD's innovative potential in the available literature by introducing insights from behavioral science through an interdisciplinary view.

3. Research Method

Notably, a conceptual framework represents a critical piece that connects theory and empirical investigation [52], [53]. Three core constructs comprise the development of our proposed model: product innovation, MPD, and designers' cognitive behavior. Each is integral to the framework's explanatory power. Product innovation, as considered in this framework, encompasses the introduction of original product architectures, the development of creative module combinations, and the ability to address heterogeneous customer demands with novel features.

As noted, an issue in the literature is the effectiveness of MPD in yielding innovative product outcomes. Further, we propose MPD's effect on the realization of product innovativeness is affected by the designer's cognitive behavior. By integrating behavioral science as a key element, our framework extends beyond conventional technical and design-centric models in the literature, allowing for a more nuanced analysis of the non-rational, human factors that moderate the relationship between MPD and innovation. This method yields novel insights and practical recommendations for addressing cognitive constraints, ultimately equipping design teams and organizations to more effectively leverage modularity for sustained innovative performance. In this regard, the framework offers a distinct contribution by capturing the interplay between modular product, innovation objectives, and the behavioral realities of design practice.

We used the narrative literature review method [54] to connect the three core research constructs and form the theoretical bases of our conceptual model. This review method was chosen for its effectiveness in synthesizing interdisciplinary knowledge. It enables the identification of prevailing research trends, gaps, and key themes across multidisciplinary domains [55], [56], by integrating behavioral science insights underpinning designers' cognitive behavior [30], [57] with the engineering principles central to MPD [5] and product innovation [58], [59]. Furthermore, this method's flexible nature without requiring a predefined research question makes it well-suited for exploring diverse, intersecting topics, supporting robust analysis of the interplay between the three constructs that shape design outcomes.

The keywords used were: modular design, modular product, modular product design, modular product development, modular product architecture, product modularity, product modularization, product modularization, product architecture modularity, modular product innovation, new modular product, designer behavior, cognitive bias, and heuristics. Articles highlighting some or all of these keywords anywhere in their content were retrieved from the Google Scholar database, chosen for its higher likelihood of providing relevant articles regardless of case sensitivity. To ensure a comprehensive and integrative outcome, we considered all document types relevant to the research aim. The final selection comprised 67 peer-reviewed journal articles, five conference papers, one book chapter, and one book. While Google Scholar was used as an initial search engine to ensure broad coverage of the relevant literature, the quality and academic rigor of the identified works were ensured through a subsequent screening process. All selected documents were cross-verified for Scopus indexing by carefully reviewing their titles, abstracts, and publication sources.

4. Conceptual Framework Development

In this section, we build on the findings in the relevant literature to critically synthesize the two research views regarding MPD's impact on product innovation and discuss how one proposes that MPD is a hindrance to product innovation while the other contends MPD enhances it. Following this discussion, we bring forward the first part of our conceptual framework. Then, we introduce the idea of how designers' cognitive thinking impacts MPD product innovativeness, after which we present our complete conceptual model.

4.1 View 1: Modular Product Design Hinders Product Innovation

The first research stream we identified in the study argues for the counterproductive (i.e., hindering) effect of MPD on product innovation – Figure 1. Product designers often rely on *established standards* and *interfaces, repeatedly reusing* modules, employing *past design experience* [4], [22], which often leads to *imitation* [15], [27], [41], [44], thereby hindering the introduction of innovative products. The research also reports that the focus on innovating *specific product modules* also limits the creativity of design teams by resulting in poor coordination and information sharing [35]. Furthermore, some researchers argue that an increase in modularity can impede product innovation, because *overly modularized* product design increases design complexity, which can limit designers' creative freedom [4], [22], [44].

Some studies offered approaches to mitigate the MPD hindering effects. For instance, Nepal et al. [60] used a fuzzy logic-based approach to reduce modularization costs through modular design. However, the design strategy still relies upon designers' judgment. Lau et al. [4] proposed the concept of an *inverted U-shape* technique to reconcile product modularity and product innovation, indicating that while modularity initially enhances innovation, *over-modularity* can significantly hinder it. Shamsuzzoha and Helo [35] attempted to resolve the barriers to modular product innovation by improving information management among designers. Thus, this stream sees MPD as innovation-hindering (Figure 1).

4.2 View 2: Modular Product Design Facilitates Product Innovation

The second research stream argues that MPD facilitates product innovation. For instance, it empowers designers to incorporate new technology into modular components, thus enabling the development of innovative products [4], [16], [61] – Figure 2. Compared to fully integral products [3], modular products provide a better solution space, simplifying the conceptual domain for designers and accelerating creativity [4], [61]. The presence of well-defined design boundaries between modules also enhances the designer's understanding, enabling them to push the limits of innovation [61].

Decoupling and recombination of modules [21], [27], [61], [62], along with standardization through a modular production strategy [42] allow designers to try multiple combinations at the same time to develop innovative modules [4], [15]. Additionally, outsourcing external innovation and research and development for MPD further supports innovation by introducing new design insights [4], [63], [64].

MPD reduces designers' cognitive load in processing information when managed properly [35], allowing them to focus on certain modular settings for

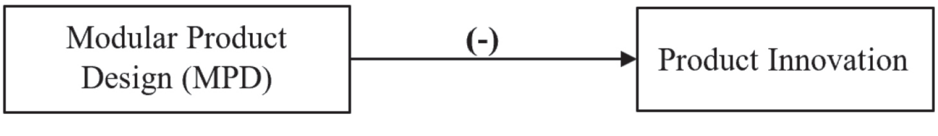

Figure 1. The hindering impact of MPD on Product Innovation (View 1)

future innovation [15]. As a result, this stream argues that MPD is essential for innovation, as it eases communication among designers, facilitates the retrieval of proposed modules, and addition of new ideas. This, in turn, simplifies the introduction of new modular design into the product development process. Thus, this second research stream sees MPD as innovation-facilitating (Figure 2).

While the arguments of this research stream are persuasive, they do not negate the arguments offered by the first research stream and vice versa.

4.3 Product Designer Cognitive Behavior

Findings from the previous two sub-sections clearly show that there are two opposing views when it comes to MPD effects on product innovation. These are innovation-hindering (sub-section 4.1) and *innovation-facilitating* (sub-section 4.2) views represented through distinctive research streams. However, the available literature does not offer an answer as to how to reconcile these contradictory findings. In this section, we assess the modularity-innovation contradiction through the lens of behavioral science. Specifically, we argue that designers' cognitive behavior can moderate or reconcile these opposing literature findings. Therefore, based on our research objective we propose the following:

Designers' cognitive behavior moderates modular product design's impact on product innovation.

We proceed to discuss the literature that can address designers' cognitive behavior in the field of product innovation and MPD. This way, we help in reducing the lack of literature on the interaction between them. We argue that innovation in the MPD process is influenced by product designers' cognitive behavior and decision-making strategies. Specifically, MPD is limited by design heuristics (e.g., heuristics causing a negative effect during the design process) [65]. The existence of heuristics (or mental shortcuts) and the resulting cognitive biases emphasize the need to confirm and further explore their role in MPD and their moderating effect on product innovation.

Some researchers argue that empowering individual designers' imaginative capability through storytelling and metaphor is an established technique to shape their cognitive behavior during product design thinking [51]. In the context of MPD, storytelling could help designers adapt to the design changes by filling in the missed design information [38], [51], which could boost their ability to imagine alternative modular features beyond the *existing design experience* [51]. This aligns with the understanding that human thinking is often shaped by narratives that may not be, in fact, purely rational [32], [33]. Consequently, this cognitive thinking can amplify MPD benefits by helping designers grasp alternative design options and remember the intricate details of the modules they aim to innovate.

Utilizing metaphors further assists designers in imagining and interpreting their past design experiences with the newly proposed ones [66], [67]. This, in turn, changes designers' thinking [51] regarding which modules should be improved to enhance product novelty by reducing reliance on past design experience. Additionally, designers' cognitive behavior can also be shaped by exposing them to a design team, where diverse design thinking is reflected [28], [32], [66]. This exposure could help designers brainstorm the innovation challenges and resolve the difficult parts of their work [66], [67], while promoting comparisons of their own MPD proposals with those of others. By avoiding unproductive debates and employing counter-explanations among design teams on certain product modules, designers can also combat confirming the reliance on past experience [32], [68]. Such discussions, when guided by ethnographic data [51], could help designers extract new MPD insights and adjust their cognitive behavior accordingly.

In addition to the strategies shaping individuals' cognitive behavior, such as storytelling and metaphors, the modularity-innovation contradiction can be moderated through situational awareness [69], [70]. The MPD often centers not just on an individual's design cognition but also on how situational information is shared and interpreted across design teams. As a result, distributed situational awareness [69], [71], [72] enables designers to achieve collec-

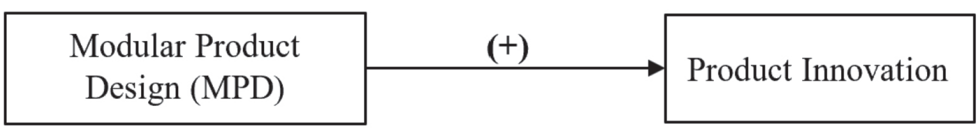

Figure 2. The facilitating impact of MPD on Product Innovation based on the existing literature (View 2)

tive awareness, thereby mitigating cognitive behavior that limits their ability to innovate modular products. This approach complements our focus on individual design heuristics by highlighting how group-level cognitive behavior can harmonize the diverse modular insights into a cohesive, innovative product feature.

Engaging in a comprehensive assessment of the entire attributes of a modular product can encourage designers to alter their cognitive behavior during design process. This would enable designers to generate an improved MPD with increased objectivity to reduce the impact of availability bias that may arise from reliance on *past experiences*. Similarly, this notion worked in design thinking for innovation [51], [68]. Moreover, the consideration of manageable multiple-modular designs, as opposed to the notion of over-modularity, for specific product sections, serves to mitigate confirmation bias that previously established design standards are consistent [73], [74]. This notion was supported by an experiment conducted by Yilmaz et al. [75] in which design students were asked to create multiple designs for a specific object, enabling them to generate new alternative designs.

4.4 Conceptual Framework Development

Our conceptual framework is represented by Figure 3. In effect, the hindering and facilitation effects (Figures 1 and 2) are replaced by the designers' cognitive behavior, which can have either one of the aforementioned effects. Thus, MPD is the independent variable, product innovation is the dependent variable, and designers' cognitive behavior is the moderating variable.

Thus, designers' cognitive behavior is a moderating variable that determines if the MPD will result in product innovativeness. As for the authors knowledge, the present study is the first to identify the influence of designers' cognitive behavior on this relationship. Thus, we expect that this contribution will provide a new and fresh vision of the dynamics between these three constructs.

5. Discussion and Conclusions

The present study recognizes and emphasizes the significant role of designers' cognitive behavior in MPD and its impact on product innovation. An examination of both theoretical frameworks and literature findings shows that designers' mental shortcuts (e.g., availability heuristics), particularly the reliance on past design experience, could give birth to a cognitive bias (e.g., confirmation bias) that can limit alternative MPD and hinder product innovation. However, behavioral science literature remains, until this research, largely separated from MPD literature. Specifically, the main contribution of the present study is the developed conceptual framework, which states that: *Designers' cognitive behavior moderates modular product design's impact on product innovation*. Our findings contribute to both theoretical and practical applications in the field of MPD and product innovation.

Theoretical Implications: This study – and specifically the conceptual framework – expands the understanding of how cognitive behavior interacts with MPD to influence product innovation. Drawing on the behavioral economics foundation of Tversky and Kahneman [30], [31] and Thaler [32], as well as its later application to product innovation [28], [51], [76], this study highlights that an unmanaged cognitive behavior can lead to non-optimal design decisions. Moreover, we argue that the lack of attention to behavioral science during the MPD can explain the existence of two opposing research MPD views that support innovation-hindering or innovation-facilitating stands (sub-sections 4.1 and 4.2). We hope that this insight will encourage researchers to conduct further empirical investigations into the impact of designers' cognitive behavior on product innovation through MPD.

Practical Implications: For designers, this study provides crucial insights for enhancing MPD product innovation through a better understanding of the negative effect of cognitive behavior that often stems

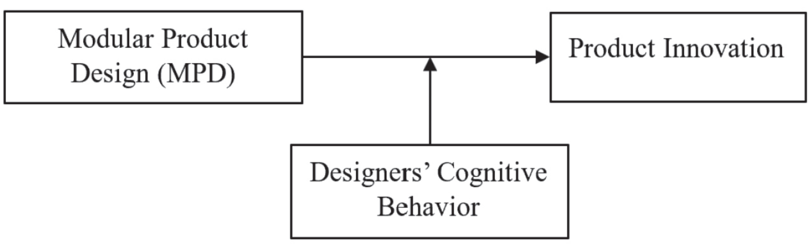

Figure 3. Developed conceptual framework: Designers' Cognitive Behavior Moderates the Impact of MPD on Product Innovation

from designers' thinking style. Encouraging the use of storytelling and metaphors can shape design adaptability, enabling designers to think beyond the previously existing design experience. Additionally, fostering a collaborative environment, including teamwork, where diverse perspectives are valued, can help designers generate innovative modular products.

Limitations and Future Research: This study's main limitation is the absence of empirical testing of the developed conceptual framework, connecting MPD, innovation and designers' cognitive behavior (section 4.4, Fig. 3). Although this study attempted to explore and discuss this connection and shed light on how shaping designer's cognitive behavior in a manufacturing company can foster innovation through MPD, we have not conducted an in-depth investigation for a specific design context. Notably, the study focuses on the manufacturing sector, while modularity has also been applied in other sectors, like the off-site construction [77]-[79]. Thus, the future research should highlight the broader applicability of modularity-innovation and designer cognitive behavior across diverse industry sectors.

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