# Technology Complexity and Firm Performance: The Moderating Effect of Design Innovation

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**Abstract:** In today's highly competitive markets, firms can no longer ensure competitive advantage through the development of highly complex technologies or differentiation based solely on technological and functional factors. Simultaneously, there is growing recognition that design and aesthetic factors can contribute to firms' competitive advantage and profitability. Hence, this study examines the effects of design innovation, captured by formal design registration, on firms' financial performance. We investigated the relationship between technology complexity, design innovation, and firm performance to unveil design innovation's role in exploiting complex technologies. Our main hypothesis is that design innovation positively moderates the negative effect that technology complexity yields on firm performance. We used a unique dataset that aggregates all patent data published by US-headquartered publicly-traded firms to the parent company level. We combined this with firms' financial information and design patent data from the Computat and PATSTAT databases based on their matching firm identifier. Focusing on 1,765 US firms from 1980 to 2015, we calculated firm-level technology complexity based on the structural diversity of technologies. The results confirmed our hypotheses. This study contributes to firms' resource-based view by recognizing design as a strategic resource that firms can utilize to gain a competitive advantage and by discovering design innovation's role in generating economic profits.

**Keywords:** Design innovation, Technology complexity, Structural diversity, Patent analysis, Resource-based theory

## 1. Introduction

In today's highly competitive markets, firms constantly seek new ways to innovate and gain a competitive advantage. While technological and functional factors have traditionally been the focus of such efforts, there is growing recognition that design and aesthetic factors can also be crucial in driving financial success. Technological innovations are often complex and require significant research and development (R&D) investments, with high risks and uncertainties associated with the development of new products or processes. In contrast, design innovations, including redesigning an existing product, often in combination with minor technical improvements, tend to be more incremental and involve far less R&D efforts and uncertainty (Walsh et al., 1992). In fact, most firms rely on incremental innovations and design improvements as their primary approach to new product development. Subsequently, new products are increasingly similar in functional features, and competition is shifting towards unique designs (Talke et al., 2009).

While several studies have highlighted the effects of design innovation on firms' financial performance (Bloch, 2011; Candi and Saemundsson, 2011; Filippetti, 2011; Roper et al., 2016; Rosenfeld, 2018; Rubera and Droge, 2013), most of these studies have relied on estimations of firms' design activities based on factors such as the expenditures (Chiva and Alegre, 2009; Vinodrai et al., 2007), centrality (Galindo-Rueda and Millot, 2015; Montresor and Vezzani, 2020), and internal management of design (Filippetti, 2011; Filippetti and D'Ippolito, 2017). However, these measures do not fully capture the functional dimensions of design innovation. Alternately, design patents offer legal protections for a product's aesthetic and functional features, including its style, usability, and modularization (Filippetti and D'Ippolito, 2017). Accordingly, this study explores the role of design patents in enhancing firms' financial performance.

A growing body of research has considered the various mechanisms of how design innovation contributes to firm performance, such as in relation to the emotional and symbolic value embedded in design (Creusen and Schoormans, 2005; Hoegg and Alba, 2011), and the strategic use of design for product differentiation (Filitz and Henkel, 2016; Gemser and Leenders, 2001). While researchers have some understanding of how design contributes to firm performance, it remains unclear how design may contribute to a firm's ability to exploit and commercialize complex technologies. To address this gap in the literature, we examine the moderating effects of design innovation on the financial performance of firms, specifically in the context of complex technologies. Specifically, we argue that design innovation can act as an alternative source of profit for firms investing in complex technologies that are often associated with high levels of R&D efforts as well as market and technical uncertainty (Fleming, 2001; Fleming and Sorenson, 2001).

To test our hypotheses, we used a unique dataset from Arora et al. (2021) that aggregates all patent data published by US-headquartered publicly-traded firms to the parent company level. We combined this with firms' financial information and design patent data from the Computat and PATSTAT databases based on their matching firm identifier, i.e., the global company key (GVKEY) and the PATSTAT standardized assignee identifiers, respectively. The empirical analysis focused on 1,765 US-headquartered public firms from 1980 to 2015, for which we calculated a parent firm-level technology complexity based on the recently developed measure of structural diversity (Broekel, 2019). The results of panel generalized least square (GLS) regressions confirm our hypotheses on the direct effect of design innovation on the financial performance of firms and its moderating effect on the relationship between technology complexity and firm performance, suggesting that firms operating in technology-intensive industries need to be particularly attuned to the role of design in exploiting and commoditizing complex technologies.

The present study aims to contribute to the resource-based view of the firm by recognizing design as a strategic resource that firms can leverage to gain a competitive advantage (Barney, 1991). Additionally, our findings shed light on the potential benefits of design innovation in the context of complex technologies. Our findings offer insights that can inform firm strategies and innovation management practices by highlighting the importance of design innovation in complex technology environments.

## 2. Literature review and hypotheses

### 2.1 Technology complexity and firm performance

#### *2.1.1 The two-sided effects of technological complexity at the firm level*

Complex knowledge is more challenging to invent and learn, which, in turn, requires greater economic efforts to enter those domains (Mewes and Broekel, 2022). Hence, complex knowledge is less likely to diffuse (Ganco, 2013), making it more exclusive and valuable in economic terms (Broekel, 2019). Researchers investigating this topic have typically relied on the resource-based theory of the firm as their framework. This theory proposes that complex knowledge is not easily diffused nor imitable and therefore provides firms with a significant potential for competitive advantage (Juhász et al., 2021), and greater returns from innovations (Mewes and Broekel, 2022).

While complex knowledge is often characterized by greater economic value, it also poses challenges in terms of understanding and (re-)combining. The recombination of diverse knowledge components results in a complex knowledge base, which affects the understandability and transferability of knowledge within and outside firm boundaries (Hou et al., 2022). This argument is supported by various empirical studies observed at the firm level of analysis, which demonstrate that complex technologies are negatively associated with knowledge transfer between actors within firms (Ganco, 2013), use of external knowledge (Lane et al., 2006), and knowledge generation (Hou et al., 2022).

#### *2.1.2 Research gap and hypothesis*

Based on the preceding arguments and the conflicting evidence in the literature, we reckon that further insights could be gained by examining the impact of technology complexity on firms' financial performance. Specifically, we hypothesize that the effect of complexity on firms' financial performance will be negative. This is based on the idea that while complex technologies may offer significant potential for competitive advantage and long-term economic value due to their difficulty in imitation (Juhász et al., 2021), they may not be as effective in exploiting their knowledge base and generating short-term profitability. Complex technologies may limit a firm's options for commoditization, as they may require specific complementary assets, skills, and capabilities (e.g., skilled labor, specialized production processes, and equipment) to fully exploit and commercialize their knowledge base.

In contrast, firms with simpler technologies may have greater flexibility and ease in commoditizing their products or services, as they can leverage more widely available and transferable knowledge components. Furthermore, the complexity of a firm's knowledge limits the benefits of extensibility mechanisms, as greater complexity reduces the portion of output on which each knowledge component can be applied, thereby increasing the average cost of knowledge (Antonelli et al., 2022). Hence, the following hypothesis is proposed:

*Hypothesis 1. Technology complexity is negatively associated with firms' financial performance.*

## 2.2 Design innovation

### *2.2.1 The impact of design*

Scholars have recently devoted increasing attention to understanding how design contributes to firms' innovative performance (Montresor and Vezzani, 2020; Roper et al., 2016), financial performance (Roper et al., 2016; Rosenfeld, 2018), and organizational strategies (Micheli et al., 2018).

There is sufficient theoretical and empirical evidence supporting a positive relationship between design and the financial performance of firms (Filitz and Henkel, 2016; Hoegg and Alba, 2011). Several scholars have investigated the different roles that design and designers can play in the new product development (NPD) process and their contributions to NPD performance (Goffin and Micheli, 2010; Perks et al., 2005; Ravasi and Stigliani, 2012; Roper et al., 2016). Their findings generally confirm that design positively contributes to the novelty and success of NPD, regardless of its role (e.g., design as a functional specialization or a bridging role in NPD, and continuous involvement of design in the NPD process). The role of design in promoting the marketability of innovations is also evident in studies that assess the impact of design on firm performance based on the probability of having high shares of innovative turnover (Bloch and Graversen, 2008; Galindo-Rueda and Millot, 2015; Roper et al., 2016). Specifically, Montresor and Vezzani (2020) found that the probability of having over 50 percent of turnover from innovative offerings is 3.3 percent higher in firms where design plays a central role than in firms that do not value design.

### *2.2.2 Design patents as a proxy for design innovation*

The majority of studies that examine the effects of design innovation estimate firms' design activities based on the expenditure (Chiva and Alegre, 2009; Vinodrai et al., 2007), centrality (Candi and Saemundsson, 2011; Montresor and Vezzani, 2020), and internal management of design (Czarnitzki and Thorwarth, 2012; Filippetti and D'Ippolito, 2017).

Design patents, however, can be a more suitable indicator for assessing a firm's emphasis and devotion to design innovation for the following reasons (Dan et al., 2018). First, like patents provide patent holders the exclusive right to produce, sell, and use the invention for a certain period, design registration provides legal protection against imitation and infringement by competitors, which can lead to a competitive advantage in the market. Second, design patents are cheaper and have a shorter approval period than utility patents. Given the lower overall cost and potential benefits in reducing competition, a rational firm should prioritize pursuing design patents. Finally, design patents provide legal protection for both the aesthetic and functional features of a product, including the style, usability, and modularization of a product (Filippetti and D'Ippolito, 2017). Although there is no uniform definition nor measurement for design innovation, it is widely accepted that design is not merely the physical form of a product but is closely interlinked with the functional and technological aspects, as well as some manufacturing aspects of a product such as ease of manufacturing and efficient use of materials (Gemser and Leenders, 2001).

### *2.2.3 Research gap and hypothesis*

Overall, theoretical and empirical support exists for a positive relationship between design innovation and firms' financial performance. However, to date, this relationship has not been empirically tested on design patents across multiple industries. Thus, it remains unclear whether firms' engagement in design innovation, as measured by legal registration of design that captures both the aesthetic and functional dimensions of a product, affects the profitability of their innovations. We thus state and test the following hypothesis:

*Hypothesis 2. Design innovation is positively associated with firms' financial performance.*

## 2.3 Technology complexity and design innovation

### *2.3.1 Increased marketability and exploitation of complex technologies*

The relationship between design innovation and the marketability of innovations finds wide theoretical support in the literature (Galindo-Rueda and Millot, 2015; Montresor and Vezzani, 2020). The literature proposes that firms can enhance their capability to handle the challenges of introducing innovative products through design innovation. This enables them to gain a better understanding of consumer responses, shape their needs and preferences, and respond with innovative solutions that incorporate technological and non-technological

advancements. In this respect, design innovation may improve the marketability of complex technologies that are often characterized by higher levels of market uncertainty (Valle and Vázquez-Bustelo, 2009) by introducing products that are not just technologically advanced but also better suited to the needs and preferences of the market. Additionally, considering that complex technologies are also characterized by higher levels of R&D risks, firms can build on their existing knowledge to (re-)design products or services that are more tailored to the needs and preferences of specific customer segments such as those in niche markets or with specific functional or aesthetic needs (Gilal et al., 2022; Hemonnet-Goujot and Valette-Florence, 2022; Verganti, 2018). Hence, firms that invest in design capabilities are more likely to successfully commercialize complex technologies and achieve greater profits from their innovations.

Technology-driven radical innovations built upon a complex knowledge base are associated with greater R&D efforts, difficulties, as well as market and technical uncertainties (Valle and Vázquez-Bustelo, 2009). Conversely, design innovations, including redesigning an existing product, often coupled with minor technical improvements, involve far less R&D effort and uncertainty (Walsh et al., 1992). On this basis, firms pursuing radical innovation can reduce the uncertainty and risks associated with technological development by investing in design capabilities. In other words, design innovation may act as an alternative source of profit for firms investing their R&D efforts in complex technologies (Verganti, 2009).

#### *2.3.2 Research gap and hypothesis*

Based on the literature discussed so far, we argue that design innovation can assist firms in better utilizing their complex knowledge by transforming it into more valuable and marketable products or services. By combining their existing knowledge with design thinking, firms can develop products or services that cater to the unique requirements of different customer groups while reducing the uncertainty and risks associated with developing complex technologies. Consistent with Hypothesis 1, we contend that the negative impact that technology complexity has on firms' financial performance can be mitigated through design innovation, which helps firms leverage their existing knowledge and even successfully commercialize complex technologies. Thus, we propose the following hypothesis:

*Hypothesis 3. Design innovation positively moderates the relationship between complexity and firms' financial performance.*

## 3. Data and methods

### 3.1 Data

#### *3.1.1 Data and sources*

Figure 1 illustrates the data collection method. Using Arora et al.'s (2021) set of patent applications from PATSTAT matched to Compustat firms for the period 1980–2015 as a reference dataset, we combined data from three main sources: (i) company and financial information from the Compustat North American Database, (ii) design patent applications and additional information related to Arora et al.'s (2021) patent dataset (i.e., the Cooperative Patent Classification (CPC) and citation information) from the EPO's PATSTAT Database, and (iii) structural diversity values from Broekel (2019).

Arora et al. (2021) aggregated all patent data published by US-headquartered publicly-traded firms with active records and positive R&D expenses for at least one year from 1980 through 2015 to the parent company level, accounting for both private and publicly-traded subsidiaries. Consequently, we linked Arora et al.'s (2021) dataset with the Compustat and PATSTAT datasets based on their matching firm identifier, i.e. GVKEY and patent publication I.D.s, respectively.

Figure 1 provides a summary of all the variables and data sources. Using these data sources, we constructed a unique panel dataset comprising 16,888 firm-year-level observations for 1,765 firms. These observations were made over a 35-year period spanning from 1980 to 2015. It should be noted that the dataset is an unbalanced panel, as the data for each variable does not cover an identical time frame.

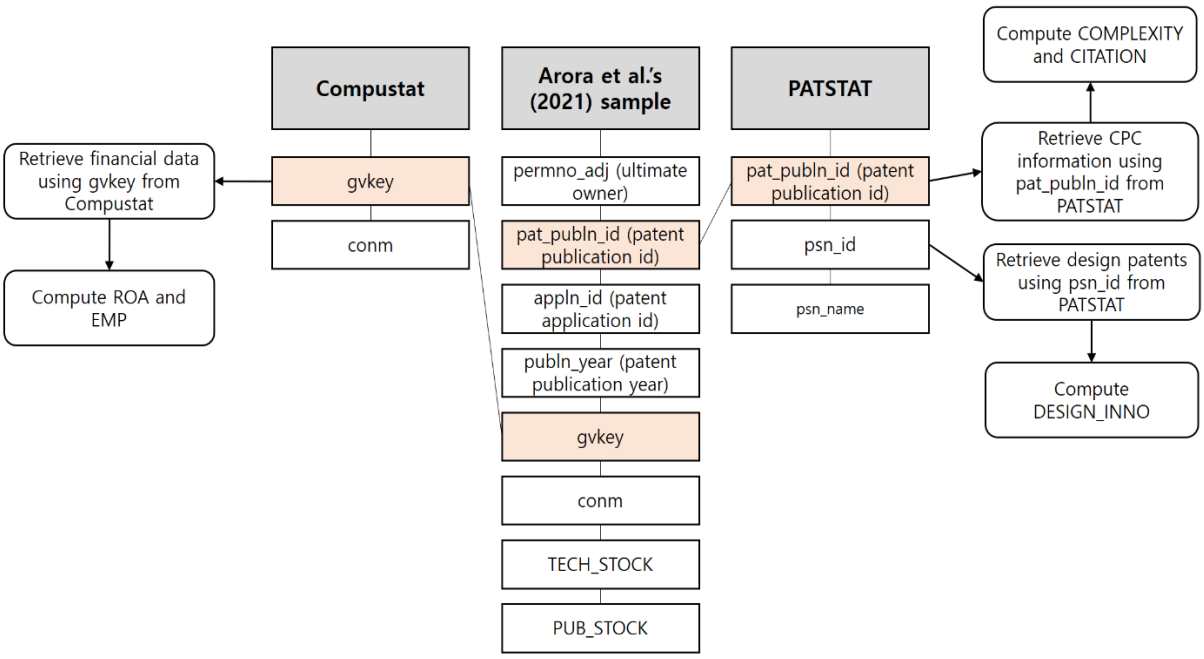


**Figure 1: Framework of data collection for analysis**

## 3.2 Variables

### *3.2.1 Financial performance (ROA)*

We measured a firm's financial performance in a given year by its returns on assets (ROA). This is calculated by dividing the net income by the average total assets.

### *3.2.2 Technology complexity (COMPLEXITY)*

Following Broekel (2019), we used a measure of a firm's technology complexity based on its patent portfolio. Specifically, the technology complexity of a firm in a given year was determined by multiplying the number of technology patents filed by the firm within a specific technology field (4-digit CPC) by the corresponding value of Broekel's (2019) structural diversity. This resulting value was then averaged by the number of technology fields specialized by the firm to compute the average technology complexity of the firm. To account for any delayed effects associated with patents, we lagged the measure by three years.

### *3.2.3 Design innovation (DESIGN)*

We measured a firm's design innovation each year using the natural logarithm of the number of design patents. We also lagged this measure to account for delayed effects that could have led to endogeneity between the dependent and explanatory variables.

### *3.2.4 Control variables*

Following the extant literature on the impact of patenting on firm performance, we included the following control variables that may be correlated with firms' financial performance, design innovation and technology complexity. First, we introduced an input measure of innovation—the stock of patents (TECH_STOCK)—to control for the impact of technology patents. Second, previous studies have empirically demonstrated the significance of firm size on technology development (Tyler and Steensma, 1998). Therefore, we included the number of employees (EMP) as a proxy for firm size to account for potential economies or diseconomies of scale. Third, to control for the importance or value of patents, we included the number of citations (CITATION) in our model. Finally, as scientific and technological discoveries are not always patented, we included the number of scientific journal publications (PUB_STOCK) to control for firms' innovation efforts that are not captured by patents. All control variables were lagged and log-transformed.

**Table 1: Description of variables**

| Variables | Abbreviation | Description | Data source |
|---|---|---|---|
| Financial performance | ROA | The percentage of net income divided by the average total assets | PATSTAT |
| Technology complexity | COMPLEXITY | The average complexity of technologies possessed by firm *i*, computed with Broekel (2019)'s value of structural complexity | PATSTAT, Broekel (2019) |
| Design innovation | DESIGN_INNO | The number of design patents filed by firm *i* and its subsidiaries in time *t* | PATSTAT |
| Innovation quality | CITATION | The number of citations received for technology patents within 5 years after its publication | PATSTAT |
| Technology innovation | TECH_STOCK | The number of cumulative technology patents filed by firm *i* and its subsidiaries in time *t* | PATSTAT |
| Firm size | EMP | The number of employees | COMPUSTAT |
| Scientific paper publication intensity | PUB_STOCK | The number of cumulative scientific publications published by firm *i* and its subsidiaries | Arora et al. (2021) |

### 3.3 Empirical model

The empirical model is estimated using panel data spanning 1,765 firms for 35 years from 1980 to 2015, which means the estimation method needs to account for both time-variant-effects and firm-specific variations. Therefore, we used cross-sectional time-series feasible generalized square (FGLS) regressions with panel-specific first-order autoregressive (AR(1)) autocorrelation, as suggested by Cameron and Trivedi (2005). The autoregressive model specifies that the dependent variable linearly depends on each firm's previous values. This means that the error structure is specified for each firm, allowing for a panel regression model that considers heterogeneity among firms. By doing so, we can avoid issues related to time-variant and cross-sectional endogeneity (Baltagi, 2021).

## 4. Results

### 4.1 Regression analysis

Table 3 presents the regression results for design innovation. The first model contains only the control variables, while the second model presents the baseline model with only DESIGN_INNO as an independent variable. All control variables included in the estimation models are statistically significant at the 0.01 level. The number of employees (EMP), often used as a proxy for firm size, is positive and statistically significant. The number of publications (PUB_STOCK), considered a proxy for the quantity of knowledge output, also shows the expected positive sign and is statistically significant. In other words, the more scientific papers published, the higher the financial performance of the firms. The coefficients of CITATION and PATENT_STOCK are also statistically significant and positive, indicating that both the quality and quantity of patenting matter for the financial performance of firms.

As for the explanatory variables, there is a significant positive effect of DESIGN on firms' financial performance in Model 2 to 4. This supports hypothesis 1, which states that design innovation positively affects a firm's financial performance. Consistent with prior literature, these findings suggest that firms that invest in design innovation are likely to achieve better financial performance, thus highlighting the importance of considering design innovation as a critical factor in firms' innovation strategies, alongside technology innovation. By investing in both technology and design innovation, firms can enhance their competitiveness and achieve sustainable long-term growth.

Model 3 includes DESIGN_INNO and COMPLEXITY together. The coefficient of COMPLEXITY is negative and significant, supporting our hypothesis that technology complexity has a negative impact on firms' financial performance. Theoretically, this result suggests that knowledge complexity may hinder a firm's effective utilization of its knowledge resources to achieve superior financial performance.

Finally, Model 4 includes the interaction term between DESIGN_INNO and COMPLEXITY. The results are consistent with those discussed so far, and the interaction term has the expected positive impact (β = 0.058) and is significant at the 0.05 level. The coefficient of technology complexity is -0.305 ($p < 0.01$) in this model, indicating that the negative impact of technology complexity on financial performance is alleviated as design innovation increases. This implies that Hypothesis 3, suggesting that design innovation can positively moderate the negative effect of technology complexity on firms' financial performance, is supported. These findings indicate that design innovation can play a crucial role in enhancing firms' financial performance, especially in the presence of high technology complexity.

**Table 2: Generalized least square regression model for design innovation**

| | | Dependent variable: logROA | | | |
|---|---|---|---|---|---|
| | | Model 1 | Model 2 | Model 3 | Model 4 |
| Control variables | EMP | 1.164*** | 1.230*** | 1.335*** | 1.347*** |
| | | (0.014) | (0.011) | (0.009) | (0.009) |
| | PUB_STOCK | 0.331*** | 0.344*** | 0.321*** | 0.315*** |
| | | (0.011) | (0.010) | (0.009) | (0.008) |
| | CITATION | 0.045*** | 0.080*** | 0.152*** | 0.169*** |
| | | (0.006) | (0.006) | (0.007) | (0.007) |
| | PATENT_STOCK | 0.204*** | 0.229*** | 0.301*** | 0.315*** |
| | | (0.013) | (0.012) | (0.013) | (0.013) |
| Independent variables | DESIGN_INNO | | 0.032*** | 0.034*** | 0.039*** |
| | | | (0.011) | (0.012) | (0.013) |
| | COMPLEXITY | | | -0.284*** | -0.305*** |
| | | | | (0.021) | (0.021) |
| | DESIGN_INNO·COMPLEXITY | | | | 0.058** |
| | | | | | (0.024) |
| | Constant | 12.858*** | 12.583*** | 12.336*** | 12.269*** |
| | | (0.038) | (0.033) | (0.030) | (0.030) |
| N (group) | | 16,888 | 16,888 | 16,888 | 16,888 |
| | | (1,765) | (1,765) | (1,765) | (1,765) |
| Wald $\chi^2$ | | 14904.60*** | 29089.36*** | 46983.53*** | 50033.95*** |
| BP ($\chi^2$) | | 455.26*** | 455.42*** | 397.46*** | 405.41*** |

Notes: * p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors are in parentheses below the coefficients.

Figure 2 presents an interaction plot that visualizes the moderating effect of design innovation. The figure plots the relationship between technology complexity and firm performance for low, medium, and high levels of design innovation. It shows that the lower the level of design innovation, the steeper the line, suggesting that the negative impact of technology complexity on firm performance is more severe for firms with lower levels of design innovation. In other words, the negative impact of technology complexity is gradually reduced as firms engage in more design innovation activities.

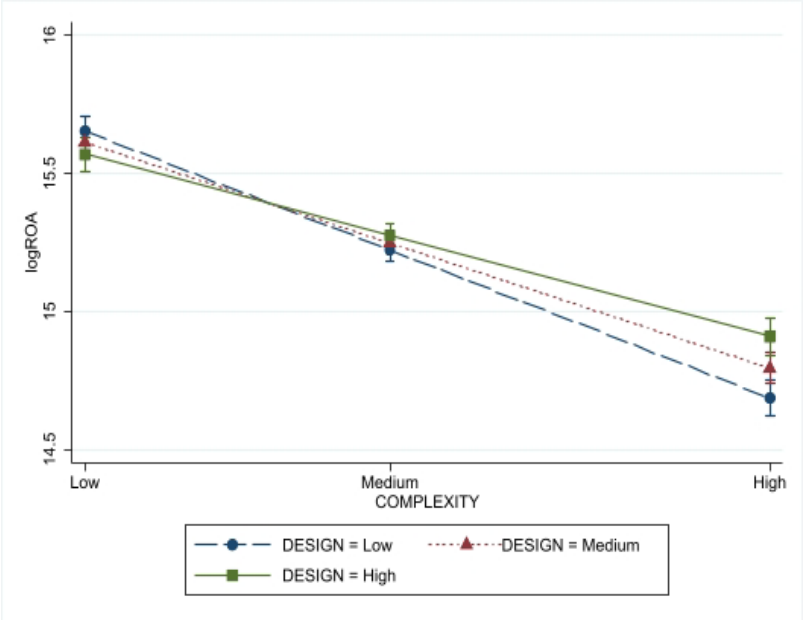


**Figure 2: Impact of technology complexity on logROA at different levels of design innovation**

## 5. Discussion and implications

### 5.1 Interrelationship of design innovation, technology complexity, and firm performance

The results of the present study suggest that design innovation plays a crucial role in enhancing the firms' financial performance. Specifically, we found that design innovation positively affects firm performance and moderates the negative relationship between technology complexity and firm performance. In other words, design innovation improves the negative effects of technology complexity on the exploitation or commoditization of knowledge stock. These findings are consistent with prior research illustrating the importance of design innovation in achieving competitive advantage and improving firm performance.

As argued by Antonelli et al. (2022), technology complexity can have both positive effects (e.g., an increase in the exploration of knowledge) and negative effects (e.g., a decrease in the exploitation of knowledge). The present study supports this view by highlighting the negative effects of technology complexity on firms' financial performance. Our results suggest that firms with higher levels of technology complexity face greater challenges in translating their technological knowledge into practical solutions that can create value for their customers. This could be due to the increased costs associated with developing complex technologies or the greater risks and uncertainties associated with the commercialization of such technologies. Consequently, firms with high levels of technology complexity may struggle to fully exploit their technological knowledge, leading to lower financial performance. Therefore, firms should balance their investment in complex technologies with efforts to effectively manage and exploit their knowledge to ensure sustained financial performance.

### 5.2 Implications

The study contributes to the resource-based view of the firm by highlighting the importance of design innovation as an important factor in driving firms' financial performance. In addition, the study offers insights into the interplay between technology complexity and design innovation, suggesting that firms operating in technology-intensive industries need to be particularly attuned to the role of design in exploiting complex knowledge and in different stages of the life cycle of a product or technology. This finding aligns with the dynamic capabilities perspective, which emphasizes the importance of firms' ability to adapt and respond to changes in their environment, such as a shift of emphasis in products from functions to forms or from technology-oriented innovation towards design-oriented innovation. From a managerial perspective, firms should invest in developing design capabilities and integrate design thinking into the product development process, particularly in technology-intensive industries. This can help firms to better exploit and commoditize their knowledge base and achieve a sustained competitive advantage.

### 5.3 Limitations and future research

There are some limitations to this study. First, it focuses on US-headquartered publicly-traded firms, which may limit the generalizability of the findings to smaller private firms and firms operating in other countries with different legal systems (i.e., intellectual property right), and market characteristics. Second, the study does not consider other factors that may influence the relationship between design innovation, technology complexity, and firm performance, such as market conditions, industry dynamics, and managerial capabilities.

A future research direction could be to explore the specific design capabilities and processes that are most effective in enhancing financial performance in the context of complex technologies. For example, researchers could investigate which types of design activities (e.g., product and brand design) are effective in improving the exploitation and marketability of technologies, and what approaches are effective in integrating design and technology development to create innovative and commercially successful products.

## References

Antonelli, C., Crespi, F., Quatraro, F., 2022. Knowledge complexity and the mechanisms of knowledge generation and exploitation: The European evidence. Research Policy, Special Issue on Economic Complexity 51, 104081. https://doi.org/10.1016/j.respol.2020.104081

Arora, A., Belenzon, S., Sheer, L., 2021. Matching patents to compustat firms, 1980–2015: Dynamic reassignment, name changes, and ownership structures. Research Policy 50, 104217. https://doi.org/10.1016/j.respol.2021.104217

Baltagi, B.H., 2021. Econometric Analysis of Panel Data, Springer Texts in Business and Economics. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-53953-5

Barney, J., 1991. Firm Resources and Sustained Competitive Advantage. Journal of Management 17, 99.

Bloch, C., Graversen, E., 2008. Innovativeness–an examination of innovative sales as a measure of innovation output.
Bloch, P.H., 2011. Product Design and Marketing: Reflections After Fifteen Years. Journal of Product Innovation Management 28, 378–380. https://doi.org/10.1111/j.1540-5885.2011.00805.x
Broekel, T., 2019. Using structural diversity to measure the complexity of technologies. PLoS ONE 14. https://doi.org/10.1371/journal.pone.0216856
Cameron, A.C., Trivedi, P.K., 2005. Microeconometrics: Methods and Applications. Cambridge University Press.
Candi, M., Saemundsson, R.J., 2011. Exploring the Relationship Between Aesthetic Design as an Element of New Service Development and Performance*. Journal of Product Innovation Management 28, 536–557. https://doi.org/10.1111/j.1540-5885.2011.00827.x
Chiva, R., Alegre, J., 2009. Investment in Design and Firm Performance: The Mediating Role of Design Management. Journal of Product Innovation Management 26, 424–440. https://doi.org/10.1111/j.1540-5885.2009.00669.x
Creusen, M.E.H., Schoormans, J.P.L., 2005. The Different Roles of Product Appearance in Consumer Choice*. Journal of Product Innovation Management 22, 63–81. https://doi.org/10.1111/j.0737-6782.2005.00103.x
Czarnitzki, D., Thorwarth, S., 2012. The Contribution of In-house and External Design Activities to Product Market Performance. Journal of Product Innovation Management 29, 878–895. https://doi.org/10.1111/j.1540-5885.2012.00935.x
Dan, S.M., Spaid, B.I., Noble, C.H., 2018. Exploring the sources of design innovations: Insights from the computer, communications and audio equipment industries. Research Policy 47, 1495–1504. https://doi.org/10.1016/j.respol.2018.05.004
Filippetti, A., 2011. Innovation modes and design as a source of innovation: a firm-level analysis. European Journal of Innovation Management 14, 5–26. https://doi.org/10.1108/14601061111104670
Filippetti, A., D'Ippolito, B., 2017. Appropriability of design innovation across organisational boundaries: exploring collaborative relationships between manufacturing firms and designers in Italy. Industry and Innovation 24, 613–632. https://doi.org/10.1080/13662716.2016.1263888
Filitz, R., Henkel, J., 2016. Competing in Design: Differentiation, Imitation, and Value Capture. https://doi.org/10.2139/ssrn.2826391
Fleming, L., 2001. Recombinant Uncertainty in Technological Search. Management Science 47, 117–132.
Fleming, L., Sorenson, O., 2001. Technology as a complex adaptive system: evidence from patent data. Research Policy 30, 1019–1039. https://doi.org/10.1016/S0048-7333(00)00135-9
Galindo-Rueda, F., Millot, V., 2015. Measuring Design and its Role in Innovation. OECD, Paris. https://doi.org/10.1787/5js7p6lj6zq6-en
Ganco, M., 2013. Cutting the Gordian knot: The effect of knowledge complexity on employee mobility and entrepreneurship. Strategic Management Journal 34, 666–686. https://doi.org/10.1002/smj.2044
Gemser, G., Leenders, M.A.A.M., 2001. How integrating industrial design in the product development process impacts on company performance. Journal of Product Innovation Management 18, 28–38. https://doi.org/10.1111/1540-5885.1810028
Gilal, F.G., Gilal, N.G., Shahid, S., Gilal, R.G., Shah, S.M.M., 2022. The role of product design in shaping masstige brand passion: A masstige theory perspective. Journal of Business Research 152, 487–504. https://doi.org/10.1016/j.jbusres.2022.08.008
Goffin, K., Micheli, P., 2010. Maximizing the Value of Industrial Design in New Product Development. Research-Technology Management 53, 29–37. https://doi.org/10.1080/08956308.2010.11657648
Hemonnet-Goujot, A., Valette-Florence, P., 2022. "All you need is love" from product design value perception to luxury brand love: An integrated framework. Journal of Business Research 139, 1463–1475. https://doi.org/10.1016/j.jbusres.2021.10.066
Hoegg, J., Alba, J.W., 2011. Seeing Is Believing (Too Much): The Influence of Product Form on Perceptions of Functional Performance. Journal of Product Innovation Management 28, 346–359. https://doi.org/10.1111/j.1540-5885.2011.00802.x
Hou, T., Li, J.J., Lin, J., 2022. Linking knowledge search to knowledge creation: the intermediate role of knowledge complexity. Management Decision ahead-of-print. https://doi.org/10.1108/MD-01-2022-0025
Juhász, S., Broekel, T., Boschma, R., 2021. Explaining the dynamics of relatedness: The role of co-location and complexity. Papers in Regional Science 100, 3–21. https://doi.org/10.1111/pirs.12567
Lane, P.J., Koka, B.R., Pathak, S., 2006. The Reification of Absorptive Capacity: A Critical Review and Rejuvenation of the Construct. The Academy of Management Review 31, 833–863.
Mewes, L., Broekel, T., 2022. Technological complexity and economic growth of regions. Research Policy, Special Issue on Economic Complexity 51, 104156. https://doi.org/10.1016/j.respol.2020.104156
Micheli, P., Perks, H., Beverland, M.B., 2018. Elevating Design in the Organization. Journal of Product Innovation Management 35, 629–651. https://doi.org/10.1111/jpim.12434
Montresor, S., Vezzani, A., 2020. Design centrality, design investments and innovation performance: an empirical analysis of European firms. Industrial and Corporate Change 29, 351–374. https://doi.org/10.1093/icc/dtz046
Perks, H., Cooper, R., Jones, C., 2005. Characterizing the Role of Design in New Product Development: An Empirically Derived Taxonomy*. Journal of Product Innovation Management 22, 111–127. https://doi.org/10.1111/j.0737-6782.2005.00109.x

Ravasi, D., Stigliani, I., 2012. Product Design: a Review and Research Agenda for Management Studies. International Journal of Management Reviews 14, 464–488. https://doi.org/10.1111/j.1468-2370.2012.00330.x

Roper, S., Micheli, P., Love, J.H., Vahter, P., 2016. The roles and effectiveness of design in new product development: A study of Irish manufacturers. Research Policy 45, 319–329. https://doi.org/10.1016/j.respol.2015.10.003

Rosenfeld, S.A., 2018. Manufacturing by Design. Economic Development Quarterly 32, 313–325. https://doi.org/10.1177/0891242418798052

Rubera, G., Droge, C., 2013. Technology versus Design Innovation's Effects on Sales and Tobin's Q: The Moderating Role of Branding Strategy. Journal of Product Innovation Management 30, 448–464. https://doi.org/10.1111/jpim.12012

Tyler, B.B., Steensma, H.K., 1998. The Effects of Executives' Experiences and Perceptions on Their Assessment of Potential Technological Alliances. Strategic Management Journal 19, 939–965.

Valle, S., Vázquez-Bustelo, D., 2009. Concurrent engineering performance: Incremental versus radical innovation. International Journal of Production Economics 119, 136–148. https://doi.org/10.1016/j.ijpe.2009.02.002

Verganti, R., 2018. Overcrowded : Designing Meaningful Products in a World Awash with Ideas. Overcrowded : Designing Meaningful Products in a World Awash with Ideas 48–48. https://doi.org/10.3280/PM2018-034012

Vinodrai, T., Gertler, M., Lambert, R., 2007. Capturing design: Lessons from the United Kingdom and Canada. pp. 65–86.