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Top management team characteristics and digital innovation: Exploring digital knowledge and TMT interfaces

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A B S T R A C T

On their journey toward digital transformation, industrial firms need to embrace digital innovation. The top management team (TMT) is expected to set the course for digital innovation, which is a challenging endeavour given the novel and cross-functional nature of digital innovation. We draw on role theory to make sense of emerging role requirements for the TMT and combine this view with upper echelon theory to hypothesize on the specific TMT characteristics that are needed for digital innovation. We first theorize that firms could benefit from TMT digital knowledge. Second, we argue that the effective utilization of TMT digital knowledge can be fostered at internal TMT interfaces, such as between the chief executive officer (CEO), respectively a chief digital officer (CDO), and other top managers. Finally, we consider the TMT hierarchical structure as a contextual factor in the stimulation of TMT integration processes by integrative CEOs and CDOs. We employ panel data regressions to a longitudinal dataset of US industrial firms and find a positive relation between TMT digital knowledge and digital innovation, on average. We additionally find evidence for the integrative roles of CEOs and CDOs. However, our findings also indicate that the CDO's integrating role can be hampered by a strong hierarchical structure in the TMT.

1. Introduction

To deal with the opportunities and threats associated with digital transformation (Verhoef et al., 2021), incumbent firms, even in industrial contexts, have placed digital innovation at the top of their strategic agendas (Björkdahl, 2020; Chanias et al., 2019). However, many industrial firms struggle to unleash its full potential (Svahn et al., 2017). Especially due to the novel and cross-functional nature of digital innovation (Bharadwaj et al., 2013; Nambisan et al., 2017; Yoo et al., 2012), the initiation and implementation of digital innovation is extremely challenging in these firms (Correani et al., 2020). To overcome these challenges, conceptual and case-based research point to the crucial influence of the top management team (TMT) (e.g., Chanias et al., 2019; Kohli and Melville, 2019). In particular, the TMT is key to lay the foundation for digital innovation due to its responsibilities in terms of recognizing digital innovation's strategic potentials, articulating its strategic relevance, and allocating resources (Floyd and Lane, 2000; Wrede et al., 2020).

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How top managers interpret and execute their roles for digital innovation is of great interest from both, an academic (e.g., Volberda et al., 2021; Wrede et al., 2020) and practice perspective (e.g., Furr et al., 2019; Westerman et al., 2012). The need for digital innovation presents a new situational demand that could change the requirements of traditional TMT roles (Nicholson, 1984) and, thus, be challenging for the TMT. First, top managers need to understand and make sense of digital innovation characteristics (Hanelt et al., 2021a; Wrede et al., 2020), which, however, require fundamentally different cognitive assumptions than those that are institutionalized in industrial firms (Henfridsson and Yoo, 2014; Yoo et al., 2012). Second, due to the cross-functional nature of digital innovation, laying its foundation requires top managers to interpret digital innovation as a shared TMT responsibility and to cope with blurring boundaries of traditional roles (Bharadwaj et al., 2013; Warner and Wäger, 2019). Such novel and potentially conflicting role transitions are known as a key issue in TMT research, as they are linked to cognitive and behavioral difficulties for top managers (Floyd and Lane, 2000).

Given these emerging role requirements for the TMT caused by digital innovation, it is important to understand which characteristics help the TMT to be successful at facilitating digital innovation (Volberda et al., 2021). Especially, the individual characteristics of top managers are critical in the interpretation and execution of their roles (Ahn et al., 2017; Chapman and Hewitt-Dundas, 2018; Hambrick and Mason, 1984). Conceptual and case-based research indicates that top managers need to be aware of and support digital innovation endeavors (Chanias et al., 2019; Hanelt et al., 2021a; Volberda et al., 2021) and thus indicates that top managers may need to adapt their individual characteristics to the emerging role requirements. However, empirical evidence on the specific characteristics needed to increase the TMT's awareness remains scarce. Moreover, research suggests that considering behavioral integration—i.e., the extent of information exchange, collaborative behavior, and decision-making participation in the TMT (Hambrick, 2007; Simsek et al., 2005)—is important to understand how individual TMT characteristics actually translate into firm outcomes (Buyl et al., 2011; Georgakakis et al., 2017; Heyden et al., 2013). Although this research provides valuable insights into TMT processes, it falls short in accounting for the specific peculiarities of digital innovation.

The purpose of this paper is to explore the influence of TMT characteristics—i.e., the needed knowledge, roles, and structures in the TMT—on digital innovation. We draw on role theory to outline transitions in TMT role requirements triggered by digital innovation. We further combine this view with upper echelon theory to hypothesize on specific TMT characteristics needed for the TMT to act effectively under these emerging role requirements. We first predict that TMTs in industrial firms could particularly benefit from digital knowledge, which is understood as individual skills and experiences of TMT members in domains that relate to digital technologies (i.e., information, computing, communication, and connectivity technologies, Bharadwaj et al., 2013). However, to do so, the TMT needs to integrate digital knowledge into TMT processes. Here, specific TMT roles, such as the chief executive officer (CEO) and chief digital officer (CDO), could be crucial. Specifically, we predict that the CEO, respectively the CDO, could establish the needed integrating mechanisms at their interfaces with other top managers. The hierarchical structure in the TMT could, however, present a decisive contextual factor as it is closely tied to behavioral expectations (Georgakakis et al., 2019). We argue that a strong hierarchical structure can create behavioral barriers for the integration processes taking place at the CEO-TMT, respectively CDO-TMT, interfaces. Fig. 1 summarizes our research framework. To test our predictions, we employ a set of firm fixed effects regressions to a longitudinal dataset of 305 US industrial firms in the period from 2005 to 2016.

Our study contributes to the TMT literature in three major ways. First, our study contributes to research on the TMT's role and needed competencies for digital innovation (e.g., Kohli and Melville, 2019; Volberda et al., 2021) by providing large-scale empirical insights regarding the TMT knowledge and structure needed for digital innovation. Second, our work complements existing literature on TMT behavioral integration (e.g., Buyl et al., 2011; Georgakakis et al., 2017) by substantiating the crucial role of integrative CEOs for behavioral integration even in the context of digital innovation. We further highlight how other TMT roles than the CEO (i.e., the CDO) can be highly beneficial for behavioral integration in the context of digital innovation. Third, our study extends the emerging research on the CDO (e.g., Firk et al., 2021; Kunisch et al., 2020; Singh et al., 2020) by informing the debate on the roles and effectiveness of CDOs. As such, our study has important practical implications for the composition and design of TMTs.

2. Background

To meet the prevalent digitalization across societies (Tilson et al., 2010), unfolding as digitalized consumer demand and competition (Verhoef et al., 2021), firms are required to engage in digital innovation. In general, digital innovation can be defined as "the creation of (and consequent change in) market offerings, business processes, or models that result from the use of digital technology" (Nambisan et al., 2017, p.224). General Motors' OnStar provides an example of such a digital innovation. OnStar builds on digital technologies, such as global positioning systems, mobile technology, entertainment and navigation systems, and on-board microprocessors, to embed novel digital services in cars, such as emergency services, roadside assistance, and in-vehicle apps, offering a very different driving experience (Yoo, 2010).[1] However, despite this example, initiating and implementing digital innovation is typically extremely difficult for industrial firms as it requires fundamental shifts in their innovation trajectories and can relate to a strategic and organizational change that alters the firms' value creation logics (Henfridsson and Lindgren, 2005; Henfridsson and Yoo, 2014; Singh et al., 2020). Hence, industrial firms are especially challenged when embracing digital innovation, with the literature indicating that two key challenges stand out.

[1] For our measurement, we rely on digital patent filings to proxy for digital innovation. Digital patent filings represent an essential foundation in the development process, but also in ensuring the continued success of digital innovation outcomes as indicated by corporate and business press regarding the example of General Motors' OnStar (General Motors, 2009, 2010; Reese, 2016).

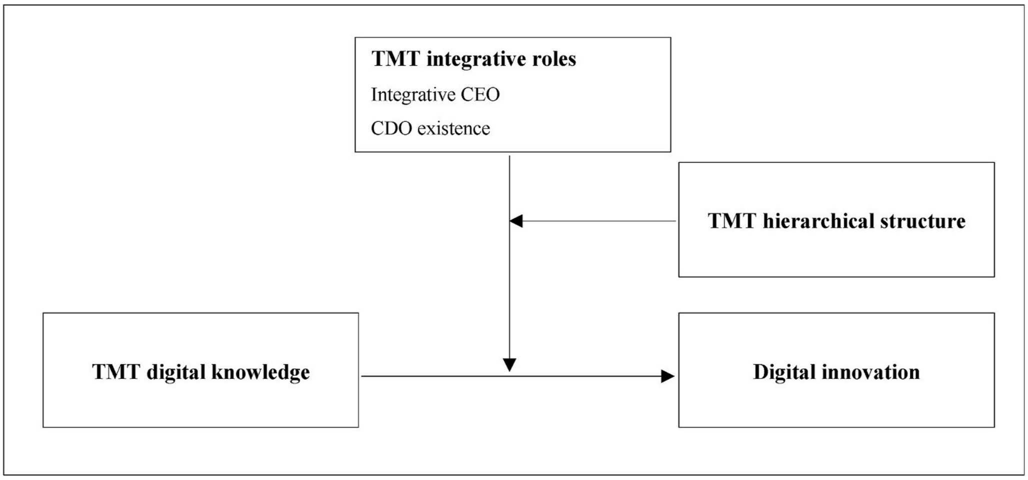

Fig. 1. Research framework.

First, many firms struggle to initiate digital innovation (Correani et al., 2020; Kane et al., 2015). Initiating digital innovation means that the firm has "to identify, assimilate, and apply valuable knowledge from inside and outside the firm regarding opportunities for digital innovation" (Kohli and Melville, 2019, p.206). This task is particularly challenging due to the fundamentally different traits of digital innovation. For example, "digital convergence" creates offerings that merge formerly separated customer experiences and industries (Lyytinen et al., 2016; Yoo et al., 2012, p.1399). Hence, to initiate digital innovation, organizational members of industrial firms need to adapt key elements of their previous innovation trajectory that are deeply rooted in the historical context of the firm such as cognitive beliefs about markets, processes, and products (Henfridsson and Yoo, 2014; Kaplan and Tripsas, 2008).

Second, many industrial firms struggle to implement digital innovation (Correani et al., 2020; Morgan, 2019). Specifically, embracing digital innovation requires developing and utilizing digital competencies even in traditional functional units (Yoo et al., 2010), which implies that industrial firms are required to establish links between existing functional units and digital units (Tumbas et al., 2018) and to overcome traditional structures (Bharadwaj et al., 2013; Nambisan et al., 2017). However, overcoming these organizational boundaries can cause major difficulties since the underlying digital business logics largely differ in terms of governance structures, capabilities, collaboration modes and customer interaction (Svahn et al., 2017). Also at General Motors' OnStar, major difficulties occurred when integrating various computing capabilities into existing car platforms (Henfridsson and Lindgren, 2005; Yoo, 2010). Consequently, industrial firms face the risk of creating decoupled digital entities that fail to achieve any business impact (Björkdahl, 2020; Morgan, 2019).

Given these challenges in the initiation and implementation of digital innovation, recent literature suggests that the TMT plays a key role in the firm's digital innovation endeavors (Chanias et al., 2019; El Sawy et al., 2016; Kohli and Melville, 2019). In particular, the TMT is required to be aware of digital innovation potentials and threats, not only to react to changes, but also to proactively initiate these changes by setting the formal context and supporting its implementation (Chanias et al., 2019; Hanelt et al., 2021a; Wrede et al., 2020). However, in these endeavors, relying on established TMT roles may be insufficient. Rather, an acknowledgment of the transitioning TMT role requirements may be required as well as an understanding of how top managers should act given these emerging role requirements (Firk et al., 2021; Volberda et al., 2021). In line with this, debates about existing TMT roles and competencies (Boyden, 2017; Furr et al., 2019; Klus and Müller, 2021) and even about new TMT roles, such as that of the CDO (Hughes, 2015; Rickards et al., 2015), are increasing. To make sense of these developments, we first draw on role theory to outline TMT role transitions triggered by digital innovation. Second, we combine this view with upper echelon assumptions to hypothesize on specific TMT characteristics that have become increasingly important in order to fulfill these emerging TMT roles for digital innovation.

3. Theory and hypotheses

Role theory concerns an important aspect of organizational life that is characteristic behavior patterns (Biddle, 1986). In general, role theory is used to describe and classify roles by presuming that people behave differently depending on their position in a social system (Biddle, 1986; Ren and Guo, 2011). Drawing on role theory can help to outline specific behavioral expectations for the members of the social system and uncover the foundational building blocks of their interactions, associations, and interdependencies (Georgakakis et al., 2019; Mathias and Williams, 2017). We focus on the TMT as a social subsystem of the organization and its roles, namely the CEO role and other TMT roles at or above the level of vice president (Carmeli and Halevi, 2009; Hambrick et al., 2015). These roles can be described by their identity—for example, the role's nature, goals, tasks, and requirements—and by their boundaries, which describe the roles' interface with the environment, such as with other top managers (Ashforth et al., 2000; Mathias and Williams, 2017).

TMT roles are delimited by their scope and specificity of responsibility. For example, while CEOs have the final and overarching decision-making responsibility, other TMT roles have a divisional or functional responsibility, such as finance, marketing, operations, and specific product divisions (Carmeli and Halevi, 2009; Hambrick et al., 2015; Menz, 2012). From a traditional perspective, a clear divisional or functional role segmentation can benefit the TMT because each top manager can focus on his or her specific role identity (e.g., its goals, tasks) and thereby specialize in specific role requirements (Ashforth et al., 2000; Nicholson, 1984). Given these specialized and clearly delimited TMT roles, traditional TMT roles can be characterized by rather distinct role boundaries (Ashforth et al., 2000). Such clear role segmentation can benefit the firm at an aggregate level by supporting incremental improvements in terms of performing each role. Especially in the industrial context, this clear role segmentation has long been beneficial due to firms' relatively stable situational demands and incremental innovation focus (Hill and Rothaermel, 2003).

However, roles are shaped by contextual factors and may change to match new situational demands (e.g., Reay et al., 2006). New situational demands can trigger transitions in underlying role identities, including self-concepts and the skills of those who take on the role, and they could lead to redefinitions of existing role boundaries (Nicholson, 1984). Especially when initiating and implementing digital innovation, sticking to traditional TMT role identities and boundaries may be disadvantageous for two reasons. First, the initiation of digital innovation is more difficult to functionalize. Since digital innovation can unfold in diverse ways, those in a TMT role must be able to comprehensively recognize and make sense of digital innovation potentials and threats (Bharadwaj et al., 2013; Hanelt et al., 2021a). Case study evidence suggests that a broad range of TMT members is required to evaluate ideas for digital innovation (Chanias et al., 2019). As such, digital innovation-related responsibilities increasingly need to be perceived as part of the identity of each TMT role. Second, the nature of digital innovation implementation is inherently cross functional (Tumbas et al., 2018). For example, the TMT needs to engage in initiatives that emphasize the relevance of digital innovation, that involve other key stakeholders, and that lead to organizational structures being redesigned (Wrede et al., 2020). These tasks require TMT members to consider digital innovation as an interrelated and shared TMT responsibility (Chanias et al., 2019) and require that the rather distinct boundaries of traditional TMT roles should become increasingly permeable.

Individuals can respond to these emerging role requirements by either adjusting personal attributes, such as mindsets, values, skills, and behaviors, or by sticking to their existing individual attributes and trying to manipulate the environment to meet their existing attributes (Bogers et al., 2018; Nicholson, 1984). While the latter will result in sticking to traditional TMT roles and will potentially be disadvantageous for digital innovation endeavors, it is important to understand which characteristics in the TMT help to adjust to these emerging TMT role requirements.

3.1. TMT digital knowledge and digital innovation

Each top manager brings his or her own characteristics to meet the specific requirements of his or her role in the TMT. One important characteristic is the cognitive base (such as knowledge or assumptions) of top managers (Hambrick, 2007; Hambrick and Mason, 1984). The cognitive base influences how top managers interpret situational demands, sense opportunities, and evaluate potential decision-making options (Hambrick and Mason, 1984). Especially in complex and uncertain strategic situations that are not "objectively knowable but, rather, are merely interpretable," individual cognitive bases can lead to different notions and evaluations (Hambrick, 2007, p.334; Hambrick and Mason, 1984; Mischel, 1977). Therefore, the individual knowledge of TMT members could be crucial in influencing how top managers make sense of and interpret their role in the TMT.

Prior literature supports the knowledge of top managers as relevant in terms of how they interpret and perform their roles. For example, prior research indicates that the general and functionally diverse skills of top managers lead to increased innovation outcomes (Custódio et al., 2019; Haynes and Hillman, 2010; Heyden et al., 2017; Kor, 2006). However, digital knowledge—understood as skills and experiences in domains that relate to digital technologies (i.e., information, computing, communication, and connectivity technologies, Bharadwaj et al., 2013)—has largely been neglected. Especially in the industrial context in which digital knowledge presents skills outside the firm's focal domain (Hanelt et al., 2021), digital knowledge has not had the greatest relevance in the TMT and has therefore only been studied to a limited extent. Moreover, there are legitimate concerns about whether digital knowledge as a specialized, technological source of knowledge is actually needed at the firm's top level. For example, digitally knowledgeable managers could fall into the trap of putting in isolated, technology-focused effort that is decoupled from the actual core business and, hence, they will be less effective in performing their role in favor of digital innovation (Furr et al., 2019).

However, digital knowledge could also be particularly beneficial for TMT members to fulfill their emerging role requirements. First, TMT members with digital knowledge may be more likely to interpret their own role in favor of digital innovation. TMT members with digital knowledge can draw on their experiences in processing, interpreting, and evaluating information related to digital innovation (Chase and Simon, 1973; Furr et al., 2012; North et al., 2009). Consequently, TMT members with digital knowledge should be better able to recognize digital innovation opportunities and understand the features and logics underlying digital innovation (Wrede et al., 2020). Hence, these TMT members will be more likely to take on digital innovation-related responsibilities as part of their role. Second, top managers with digital knowledge could increasingly encourage and support other top managers to interpret their role in favor of digital innovation. Given that expert knowledge is attributed to more influence in decision-making processes (Buyl et al., 2014), top managers with digital knowledge could motivate other TMT members to engage in digital innovation endeavors. In sum, we suggest that digital knowledge in the TMT could be beneficial for TMT role interpretations in favor of digital innovation, which, in turn, should translate into increased firm digital innovation:

H1. TMT digital knowledge is positively associated with digital innovation.

3.2. The role of TMT behavioral integration: Integrating interfaces and the hierarchical context

However, even if digital knowledge is present in the TMT, it could still reside in its functional area due to the traditional view on the subordinated, supporting role of digital knowledge (Bharadwaj et al., 2013). Moreover, traditional role boundaries could hinder other top managers from perceiving digital innovation as a shared TMT responsibility, and this could even cause tensions due to diverging perspectives (Chanias et al., 2019) and conflicting goals (Svahn et al., 2017). For example, top managers could raise concerns regarding the prospects of digital innovation success, they could hide relevant information, or they could follow their own strategies and thereby put cross-functional efforts for digital innovation at risk (Chanias et al., 2019). Hence, the translation of TMT digital knowledge for digital innovation could especially depend on the behavioral integration in the TMT—the extent of information exchange, collaborative behavior, and decision-making participation (Carmeli and Halevi, 2009; Hambrick, 2007; Simsek et al., 2005). We focus on internal TMT interfaces—understood as the purposive contact points where top managers intersect and potentially transfer influence, information, and resources (Simsek et al., 2018)—to explore how the behavioral integration of TMT digital knowledge for digital innovation could be strengthened.

3.2.1. TMT digital knowledge, integrative CEOs, and digital innovation

As the TMTs' team leaders, CEOs can substantially shape the extent of integrating various top managers into TMT processes (Buyl et al., 2011; Chanias et al., 2019; Georgakakis et al., 2017). Especially when translating TMT digital knowledge into digital innovation, an integrative CEO could be crucial due to the high complexity of the acquisition, interpretation, and understanding of the relevant information, but also to mediate potential tensions caused by blurred traditional role boundaries (Chanias et al., 2019; Tumbas et al., 2018). Hence, we understand integrative CEOs as those CEOs who interpret their role in a way that fosters the involvement of top managers with digital knowledge in TMT processes, on the one hand, and that counteracts potential role conflicts in the TMT hindering the integration of TMT digital knowledge, on the other hand. Based on these mechanisms, we argue that two aspects help CEOs to act in an integrative way.

First, CEOs need to be aware of the knowledge residing in the TMT. Shared work experiences between CEOs and TMT members could help CEOs to understand and trust other TMT members and their specific knowledge (e.g., Buyl et al., 2011; Dai et al., 2016). In turn, CEOs with shared work experiences could also be more aware of the top managers possessing digital knowledge, and hence they will be more likely to strengthen their involvement in relevant TMT processes. Second, CEOs should be able to mediate and handle potential conflicts in the TMT that could hinder the integration of TMT digital knowledge. Diverse functional experiences could help CEOs to build a dense understanding of different functional roles (Georgakakis et al., 2017). In contrast to specialized CEOs who may be inclined to follow opinions from their specialized area of expertise (Georgakakis et al., 2017; Meyer et al., 2015), CEOs with diverse functional experiences tend to be less "susceptible to functionally grounded biases and stereotypes" (Bunderson and Sutcliffe, 2002; Buyl et al., 2011, p.155). Consequently, CEOs with diverse functional experiences should be more likely to overcome potential tensions that may hinder the integration of TMT digital knowledge. Taken together, we argue that CEOs who have shared and diverse work experiences are more likely to interpret their roles in an integrative way that supports the translation of TMT digital knowledge into firm digital innovation.

H2. The positive association between TMT digital knowledge and digital innovation is stronger under integrative CEOs (i.e., who have shared and diverse work experiences).

3.2.2. TMT digital knowledge, CDO existence and digital innovation

Besides the CEO, who is often the focus of research on integrating other TMT members due to his or her powerful role, it is also possible to create a distinct TMT role dedicated to integrating other TMT members (Menz, 2012). Especially in the context of digital innovation, the emerging role of CDOs is highlighted for strengthening collaboration across functional boundaries (Haffke et al., 2016; Singh and Hess, 2017; Tumbas et al., 2017, 2018) and for linking and fostering discussions among intra-organizational key stakeholders, such as other top managers (Firk et al., 2021; Kunisch et al., 2020; Singh et al., 2020).

Recent case study evidence allows for a more nuanced picture of the CDO's role in interacting with other top managers. For example, CDOs work closely with other digital-affine top managers, such as the chief information officer (CIO) and chief technology officer (CTO), but also with more general top managers, such as the chief marketing officer (CMO) or divisional heads, to align on crucial requirements for digital innovation, such as technical conditions and customer demands (Haffke et al., 2016; Tumbas et al., 2018). Moreover, CDOs act as "bridge builders" to foster collaboration and establish links among these top managers and their activities (Firk et al., 2021; Tumbas et al., 2018). Complementing this view, the findings of Singh et al. (2020) indicate that CDOs combine different formal and informal activities to facilitate information exchange and collaboration within the TMT. For example, they lead digital steering committees and set up regular events as platforms for information exchange involving other top managers (Singh et al., 2020). Given these case study insights into these specific CDO activities, the CDO's role in transcending organizational boundaries can be particularly valuable for the integration of TMT digital knowledge into TMT processes. In sum, we expect that the CDO–TMT interface could provide an important platform for integrating digital knowledge in favor of digital innovation:

H3. The positive association between TMT digital knowledge and digital innovation is stronger under the existence of a CDO.

3.2.3. The role of the hierarchical context in TMT interactional processes

The hierarchical structure in the TMT could present a decisive contextual factor for the integration mechanisms taking place at the CEO–TMT and CDO–TMT interfaces, as it is closely linked to role expectations (Georgakakis et al., 2019). As such, how other TMT members take part in mutual and collective interaction may be affected by the hierarchical structure in the TMT (Hambrick, 2007; Hambrick et al., 2015). The hierarchical structure is described by the administrative mechanisms (e.g., hierarchical levels, pay differences) arranged in the TMT, and it determines the degree of interdependence, or respectively, the disparity of top managers (Hambrick et al., 2015).

We argue that a strong hierarchical structure makes it more difficult to effectively drive behavioral integration processes in the TMT. In particular, a higher degree of hierarchical disparity among top managers could establish behavioral barriers to the stimulation of integration processes. Accordingly, even if CEOs or CDOs bring top managers together, the top managers could resist engaging in intensified information exchange or collaborative behavior due to the expectations inherent in their structurally determined roles (Buyl et al., 2011). For example, in workshops or meetings set up by the CEO or CDO, top managers with digital knowledge could hold back on giving their opinions in order to avoid any violations of the roles that are structurally conditioned for them and other top managers. Especially in the context of digital innovation, where collaborative efforts may exceed the top managers' traditional areas of responsibility (Svahn et al., 2017), CEOs or CDOs could face difficulties when trying to establish integration processes in the TMT under strong hierarchical structures. Thus, we expect that a strong hierarchical structure will negatively impact the effectiveness of CEOs and CDOs in integrating TMT digital knowledge for digital innovation:

H4. The moderating effects of an integrative CEO and the existence of a CDO are less pronounced in TMTs with a strong hierarchical structure.

4. Methodology

4.1. Sample

We focus on a longitudinal sample of industrial firms in the period from 2005 to 2016.[2] We consider the firm years of industrial firms that have been listed at least once in the S&P 900 Index (i.e., the S&P 500 LargeCap or the S&P 400 MidCap) in the period from 2005 to 2014. Industrial firms are defined as firms in industries that are heavily focused on manufacturing physical products. Similar to other studies (e.g., Nadkarni and Chen, 2014; Rai et al., 2006), we therefore follow the Standard Industrial Classification (SIC) and only include firms that belong to the manufacturing division (i.e., SIC 20–39). From this initial sample, we exclude (1) firms related to the industry group "Computer and Office Equipment" (357) due to their familiarity with digital technologies; (2) observations with missing financial or other relevant data for regressions; and (3) firms that did not file at least one patent during the period of observation (Custódio et al., 2019). The resulting sample consists of 305 industrial firms and 2413 firm-year observations.

We decided to focus on this sample for two main reasons. First, embracing digital innovation means coping with a specific type of strategic change for industrial firms, as their value-creation logics and business scope can be altered (Singh et al., 2020). Therefore, industrial firms are particularly challenged in setting a new digital innovation course (Hanelt et al., 2021; Svahn et al., 2017). Second, our focus on industrial firms allows us to concentrate on patenting as a proxy for digital innovation. Industrial firms possess a long history of patenting (Cohen et al., 2000). Hence, in patent-intensive industries, digital innovation should also be related to digital patents (Hanelt et al., 2021).

4.2. Dependent variable: Digital innovation

To proxy for the firm's digital innovation outcomes, we use data on the firm's digital patent filings. While patent activities generally allow for insights into the technological prioritization of firms (Griliches, 1990; OECD, 2009), they have also been used in the specific context of digital innovation (Hanelt et al., 2021). In the context of digital innovation, practical evidence also suggests that patenting presents a crucial competitive action to build market entry barriers for digital businesses (Parker et al., 2016). Even though digital business models cannot be patented *per se* as patent applications need to fall under a patentable subject matter (Marco et al., 2015; WIPO, 2019), algorithms can be patented and can thus be used to protect the key resources of digital business models. Also in the case of General Motors' OnStar, digital patent filings present as an essential foundation in the development process, but they also ensure the continued success of OnStar services, as indicated by the corporate and business press (General Motors, 2009, 2010; Reese, 2016). Given these arguments (e.g., Svahn et al., 2017; Yoo et al., 2010), we believe that digital patent filings are a valuable proxy for the firm's digital innovation outcomes in the industrial context.[3]

Similar to other studies examining patent data (e.g., Balsmeier et al., 2017; Custódio et al., 2019), we use data from the US Patent and Trademark Office (USPTO) (Graham et al., 2015; Marco et al., 2015). We use the raw patent data provided by the USPTO for

[2] Our dependent variable (digital innovation) presents a forwarded variable over the next two years. We therefore use observations from 2006 to 2016 to measure our dependent variable. For the measurement of our independent and control variables, we rely on observations from the period 2005 to 2014.

[3] We have conducted additional tests to assess the appropriateness of our digital innovation measure based on digital patent filings by examining whether digital patent filings are associated with more digital market offerings. Specifically, we examined the relationship between digital patent filings and news on digital and non-digital product or service releases (based on data from the Ravenpack database) and also tested the relationship between non-digital patent filings and news on both digital and non-digital product or service releases (placebo test). Our results indicated a significant positive association between digital patent filings and news on digital product or service releases, while the other relationships remained insignificant, thus supporting the use of digital patent filings as a valuable proxy in the context of digital innovation.

January 2020. Nevertheless, we needed to restrict our use of this data up to 2016, as later years suffer from truncation bias given that the time gap between the filing of the patent and its publication can take many years (Graham et al., 2015). To link our sample firms with the applicant firms in the patent data, we use a name-matching algorithm. Here, we consider that patents may be filed by different corporate entities (i.e., subsidiaries) (Belenzon and Berkovitz, 2010) and that firms may acquire other firms or divest subsidiaries over time. We further consider abbreviations of the names of our sample companies and check for name changes that occurred within our period of analysis (Magerman et al., 2006). We further execute an extensive harmonization procedure to harmonize the names of the patent applicants with the names of our sample companies by cleaning the patent applicants' names for the most common misspellings and other irregularities (e.g., spellings of the legal form, punctuation, character irregularities) (Magerman et al., 2006; Peeters et al., 2010).[4] Afterwards, we employ the *matchit* command in STATA, which allows for an algorithm-based approximating match between the names of the patent applicants and the names of our sample companies (Raffo and Lhuillery, 2009). As this matching algorithm is based on an approximate match and company names may overlap with other companies, we finally check these matches manually for appropriateness.

After matching patent information to our sample companies, we follow other scholars by focusing on regular, non-provisional utility filings (Lemley and Sampat, 2008, 2010). We further exclude filings that are not intended to assign a patent, for example, name changes made to a patent (Graham et al., 2015; Marco et al., 2015). To identify digital patent filings, we only consider specific technological classes of the US Patent Classification (USPC) scheme that are related to digital technologies. First, we consider the technological domain of "Communications & Computers," similar to Hall et al. (2001). Second, we consider technological classes that were newly created after the initial year of defining this technological domain in 2001 and that are clearly associated with digital technologies, such as "Data processing: software development, installation, and management." For example, the patent US8856536B2 filed by General Motors in the context of OnStar is classified in the USPC class 713 "Electrical computers and digital processing systems, " and thereby it was coded as a digital patent filing. Table A1 in the Appendix summarizes the USPC classes used for our operationalization of digital innovation. Finally, we consider the average number of digital patent fillings over the next two years and use, similar to prior studies (Balsmeier et al., 2017; Custódio et al., 2019; Hanelt et al., 2021a), the natural log transformation for the final *digital innovation* variable. The assignment to a certain year is always based on the filing date.

4.3. Independent variable: TMT digital knowledge

To capture the digital knowledge in the TMT, we use information from the BoardEx database. We use data sources such as Bloomberg, company press releases, and LinkedIn for manual checks of appropriateness. We start by defining which managers compose the TMT. We follow Hambrick et al. (2015), who consider managers as TMT members when they hold the title of executive vice president, senior vice president, and—in cases where a TMT consisted of only five or fewer members—vice presidents. Since this definition does not necessarily include important functional roles, such as the CIO, we further include executives with CxO titles under the restriction that there is no indication in the title for operating at a lower organizational level (i.e., "division" in the role name). We further exclude the CEO and CDO, as these top managers reflect separated variables in our model.

Next, we build our TMT digital knowledge variable by identifying TMT members with experience related to digital technologies in prior employment. Specifically, we consider top managers who have worked in a functional position or industry related to digital technologies before entering their current position (van Peteghem et al., 2019). We therefore searched through their employment history and defined positions as related to digital technologies if they included terms such as "CIO," "CTO," "information," "comput," "software," "e-commerce," "IT," "technolog," "digital," and "CDO." To ensure that these functional experiences—i.e., the experiences in a CTO position—are indeed related to digital technologies and not focused on other technologies, we carefully hand-checked for appropriateness by using additional sources such as Bloomberg, company press releases, and LinkedIn. For experience in digital-related industries, we use the BoardEx industry classification and consider the "software & computer services," "telecommunication services," and "media & entertainment" industries as related to digital technologies. We further perform a textual search on the company name for digital-related terms such as "digital," "online," or "internet," if the industry classification is unavailable for a firm (see van Peteghem et al., 2019). Finally, we count the TMT members with experience in either positions or, for at least three years, in industries related to digital technologies and mean-centered it to build our *TMT digital knowledge* variable.

4.4. Moderator variable: Integrative CEO

To account for an integrative CEO, we build on prior studies (Buyl et al., 2011; Georgakakis et al., 2017). Specifically, we consider the shared experiences of CEOs with other top managers and the functional diversity of CEOs' prior work experiences. Again, we use information from the BoardEx database. First, CEOs' shared experiences with other top managers is calculated as the pairwise overlap in tenure between the CEO and the other TMT members (Buyl et al., 2011; Georgakakis et al., 2017). Specifically, the calculation is rooted in Carroll and Harrison's (1998) formula expressed as $1/n\sum_{i\neq j}\min(u_i,u_j)$, where u is the tenure (in years) of each top manager i, j is the CEO, and n is the number of TMT members. Second, to calculate the CEOs' functional diversity, we searched through their prior employment history for functional career experiences. We define "accounting and finance," "administration and legal," "human

[4] We also used STATA codes provided by the NBER on name standardization routines under the following link: https://sites.google.com/site/patentdataproject/Home/posts/namestandardizationroutinesuploaded (last visited: May 3, 2020).

resources," "information systems and technology," "marketing," "operations," "research and development," and "strategy" as relevant functional areas of experience (Menz, 2012). We count the number of CEOs' experiences in functional areas (e.g., up to eight areas). Afterwards, we build a categorical variable, where one indicates that the CEO has experience in more than one functional area, two indicates that the CEO has experience in more than two functional areas, and three indicates that the CEO has experience in more than three functional areas. To finally calculate the values for our variable *integrative CEO*, we standardize the shared experiences of CEOs with other top managers and the functional diversity of CEOs' prior work experiences and aggregate the standardized values.

4.5. Moderator variable: CDO existence

To gather information on the existence of a TMT position holding a responsibility for orchestrating and coordinating digital innovation and/or digital transformation endeavors (Singh and Hess, 2017; Tumbas et al., 2017), we follow prior literature (Firk et al., 2021; Kunisch et al., 2020) by combining data from multiple sources. First, we examine the BoardEx database for the existence of CDOs by searching for employment related to the keywords "digital" and "CDO." Similar to prior literature (Firk et al., 2021; Kunisch et al., 2020), we exclude employments that does not match our understanding of CDOs by, for example, excluding CDOs representing the role of a chief diversity officer. In a second step, we manually collect further information on the presence of CDOs from sources such as Bloomberg, company press releases, and LinkedIn by searching for keywords such as "chief digital officer," "digital director," "digital officer," and "head of digital." Here, we check all available descriptions and, for example, exclude CDOs if the description indicates an operative role that is not linked to frequent interactions with other TMT members.[5] Our final variable of *CDO existence* is set at one if there is a CDO position, otherwise zero.

4.6. Moderator variable: TMT hierarchical structure

To calculate whether there is a strong or flat hierarchical structure in the TMT, we calculate an aggregated index composed of two hierarchy indicators. First, we used BoardEx data and follow Hambrick et al.'s (2015) procedure to measure the vertical levels among the top managers. This measure reflects the aggregated value of (1) the number of distinct hierarchical levels in the TMT by counting the number of title gradations (i.e., CEO, chief operating officer, executive vice president, senior vice president, and possibly vice presidents), and (2) the presence of a chief operating officer, indicating whether there was this additional level in the TMT (Hambrick et al., 2015). Both components are standardized into one measure. Second, we calculate the disparity of the top managers in terms of their short-term pay (defined as the sum of salary and bonuses) based on data from the ExecuComp database. Specifically, we calculate the coefficient of variation in the short-term pay among the TMT members included in ExecuComp (Fredrickson et al., 2010; Hambrick et al., 2015; Hart et al., 2015). Afterwards, we standardize these two indicators, aggregate them, and define the values above (below) the median as indicating a *strong (flat) hierarchical structure*.

4.7. Control variables

We include several control variables on the firm, CEO, TMT, and governance levels. Table A1 in the Appendix provides detailed information on the data sources and calculations. In the following, we explain the reasoning behind our selection. At the firm level, we include *firm size*, *R&D intensity*, and *return on assets,* as these may influence the capacities for innovation activities (e.g., Heyden et al., 2017b). *Capital expenditures* and *leverage* are included to account for financial constraints for innovation endeavors (Balsmeier et al., 2017; Hanelt et al., 2021). We also include *capital intensity* to control for the manufacturing intensity and *Tobin's Q* to control for growth opportunities (e.g., Custódio et al., 2019).

On the CEO level, we include *CEO educational level* as an indicator of generic skills (Georgakakis et al., 2017; Pegels et al., 2000) that are associated with innovation outcomes (Custódio et al., 2019). We further include *CEO equity compensation* to control for long-term incentives that may be related to more digital innovation efforts. Finally, we control for *CEO age*, for *CEO tenure,* to capture career incentives to engage in digital innovation (e.g., Belenzon et al., 2019; Lee et al., 2018), and for *CEO duality,* to capture the power of CEOs (Heyden et al., 2017).

On the TMT level, we control for *TMT horizontal interdependence,* as it may also influence the interactions taking place in the TMT (Hambrick et al., 2015). We further capture if there is a chief innovation officer in the firm (*CINNO existence*) that may simultaneously contribute to behavioral integration. Further, we control for the average *TMT educational level*, the average *TMT age,* and the *TMT size* (Georgakakis et al., 2017; Simsek et al., 2005) to capture further structural TMT conditions that may be related to TMT digital knowledge, TMT collaboration, and digital innovation outcomes.

On the governance level, we control for board-related variables by integrating *board size*, *board diversity*, and *board independence,* as boards may influence TMT composition and innovation endeavors (e.g., Hillman and Dalziel, 2003). We also include a control variable for *institutional ownership,* as it may affect (digital) innovation efforts (Aghion et al., 2013).

[5] We also performed an additional test that shows that our results remain robust if we only focus on the CDO observations according to the BoardEx database.

4.8. Method of analysis

To analyze our longitudinal sample, we decided to employ firm fixed effects regression models similar to prior innovation studies (Balsmeier et al., 2017; Custódio et al., 2019). The firm fixed effects regression considers any time-invariant unobservable firm characteristics, thereby allowing us to adequately control for unobserved heterogeneity and to mitigate omitted variable concerns (Wooldridge, 2010). The appropriateness of a firm fixed effects model is supported by a Hausman test (comparing a fixed effects regression to a random effects regression). Moreover, to address reverse causality concerns, we forward our dependent variable by considering digital patent filings in the subsequent two years. Finally, we also include year fixed effects to control for economic-wide shocks as well as truncation biases inherent to patent variables. To operationalize our fixed effects models, we employ the *xtreg* command in STATA by specifying the within firm fixed effects option as well as "robust" or empirical standard errors as otherwise, in cases of model misspecification or overdispersion, model-based standard errors may be incorrect. To investigate H1, we estimate the following model:

I. $$Digital\ innovation_{i,(\varnothing t+1,t+2)} = \alpha + \beta_1(TMT\ digital\ knowledge)_{i,t} + \gamma(Controls)_{i,t} + T_t + X_i + \varepsilon_{i,t}s$$

To test H2 and H3, we interact our independent variable of *TMT digital knowledge* with the moderator variables of *integrative CEO*, and respectively, *CDO existence*. Thus, we estimate the following model:

II $$Digital\ innovation_{i,(\varnothing t+1,t+2)} = \alpha + \beta_1(TMT\ digital\ knowledge)_{i,t} + \beta_2(TMT\ digital\ knowledge^*Y)_{i,t} + \beta_3(Y)_{i,t} + \gamma(Controls)_{i,t} + T_t + X_i + \varepsilon_{i,t}$$

To examine H4, we analyze the interaction between *TMT digital knowledge* and each moderator variable in sub-samples of a strong, and respectively, flat hierarchical structure. In all equations, the items besides the dependent, independent, and control variables comprise year dummies (T_t), the moderator variables (Y), the constant term (α), the firm-specific effects (X_i), and the error term (ε_{it}).

5. Results

5.1. Descriptive statistics

To illustrate the development of digital-related variables in our sample, Table 1 provides an overview of the average digital patent filings, TMT digital knowledge, and CDOs by year. Table 1 shows that digital patent filings rose to the highest value in the most recent years. We observe a similar trend in the firm's TMT digital knowledge. Regarding the existence of CDOs, we find that 38 of our sample firms appointed a CDO. Similar to our other digital-related variables, most firms appointed a CDO in recent years, leading to the highest value of CDO observations in recent years (see Table 1). Taken together, these results support the idea that digital innovation endeavors are becoming increasingly relevant for industrial firms (e.g., Svahn et al., 2017).

In Table 2, we provide further insights into the data underlying our calculations by showing the summary statistics of our regression variables. In Table 3, we provide the cross-sectional correlation matrix of all our regression variables. As the cross-sectional correlations between our regression variables are all below critical thresholds, we see no clear indication for multicollinearity from this analysis. This was further supported by checking the variance inflation factors (VIFs) while considering the multiple interaction terms. The highest individual VIF amounted to 2.65, and the mean VIFs of the regression models were all below 2. The analysis further alleviated multicollinearity concerns.

Table 1
Means of main digital variables by year.

Year	Obs.	Digital innovation (t+1 and t+2)[a]	TMT digital knowledge[b]	CDO existence
2005	218	9.72	0.85	1%
2006	235	9.77	0.89	2%
2007	251	8.49	0.94	2%
2008	258	7.84	0.95	3%
2009	247	8.88	0.99	2%
2010	254	9.69	1.05	3%
2011	246	9.76	1.18	5%
2012	245	9.92	1.20	7%
2013	235	10.78	1.27	9%
2014	224	11.43	1.23	12%
Total	2413	9.59	1.05	5%

a) Average number of digital patent filings in t+1 and t+2. In the regressions, we use a log-transformation of this variable. b) Number of top managers in the TMT possessing prior experiences in a digital technology-related position or industry. We use the mean-centered values of TMT digital knowledge in our regression analyses.

Table 2
Descriptive statistics of regression variables.

Variables	Firm-years	Firms	Mean	Std.	Min	Median	Max
(1) Digital innovation[a]	2413	305	0.87	1.25	0.00	0.41	6.35
(2) TMT digital knowledge[b]	2413	305	0.00	1.03	−1.05	−0.05	3.95
(3) Integrative CEO[c]	2413	305	0.00	1.00	−1.54	−0.21	5.63
(4) CDO existence	2413	305	0.05	0.21	0.00	0.00	1.00
(5) CEO educational level	2413	305	3.13	1.04	1.00	3.22	5.00
(6) CEO equity-based compensation[d]	2413	305	0.51	0.37	0.00	0.51	1.00
(7) CEO age[a]	2413	305	4.04	0.10	3.71	4.06	4.38
(8) CEO tenure[a]	2413	305	1.51	0.75	0.00	1.55	3.99
(9) CEO duality	2413	305	0.62	0.48	0.00	1.00	1.00
(10) CINNO existence	2413	305	0.04	0.21	0.00	0.00	1.00
(11) TMT horizontal interdependence	2413	305	−0.12	0.29	−0.61	−0.15	3.27
(12) TMT educational level	2413	305	2.98	0.44	1.00	3.00	4.67
(13) TMT age[a]	2413	305	3.98	0.06	3.71	3.98	4.30
(14) TMT size[a,f]	2413	305	2.52	0.41	1.61	2.48	3.47
(15) Board diversity[d]	2413	305	0.16	0.10	0.00	0.17	0.60
(16) Board independence[d]	2413	305	0.51	0.26	0.00	0.55	1.00
(17) Board size[a,f]	2413	305	2.28	0.20	1.79	2.30	2.64
(18) Institutional ownership[d]	2413	305	0.47	0.18	0.00	0.49	1.01
(19) Firm size[a,f]	2413	305	14.99	1.28	12.15	14.88	18.15
(20) Capital expenditures[e]	2413	305	0.04	0.03	0.00	0.03	0.24
(21) R&D intensity[f]	2413	305	0.04	0.06	0.00	0.02	0.31
(22) Tobin's Q[e]	2413	305	2.09	1.23	0.58	1.71	9.84
(23) Capital intensity[e]	2413	305	0.52	0.32	0.01	0.43	1.76
(24) Return on assets[e]	2413	305	0.08	0.08	−0.21	0.08	0.34
(25) Leverage[e]	2413	305	0.25	0.15	0.00	0.24	0.84

a) Log-transformed. b) Mean-centered. c) Standardized. d) Measured in percent. e) Winsorized at 0.01 and 0.99 levels. f) Winsorized at 0.03 and 0.97 levels. Notes: Digital innovation captures the average digital patent filings of t+1 and t+2; all other variables measured in t.

5.2. Regression results

To test our hypotheses, we employ a series of fixed effects regression models that are presented in Table 4. Regarding H1, stating that TMT digital knowledge is positively associated with digital innovation, we find empirical evidence for this prediction, as Model 1 indicates a significantly positive effect from TMT digital knowledge ($p < .05$) and an average increase of 5.4% in digital innovation if the number of top managers with digital knowledge increases by one.

Model 2 tests H2, which predicts a positive impact of the interplay between TMT digital knowledge and an integrative CEO on digital innovation. As the effect of the interaction term for TMT digital knowledge and an integrative CEO is significantly positive on digital innovation ($p < .05$), the results of Model 2 support the prediction of H2. One additional top manager with digital knowledge under a more integrative CEO (mean plus one standard deviation) is associated with an average increase of 9.3% in digital innovation. Moreover, Model 3 tests H3, which predicts a positive impact of the interplay between TMT digital knowledge and CDO existence on digital innovation. Given that Model 3 indicates a significantly positive effect of the interaction term between TMT digital knowledge and CDO existence on digital innovation ($p < .05$), our results support H3. One additional top manager with digital knowledge under the existence of a CDO is associated with an average increase of 19.9% in digital innovation. Figs. 2 and 3 visualize the interaction effects of TMT digital knowledge and an integrative CEO, and respectively, CDO existence on digital innovation. In addition to that, it is interesting to see that we find an insignificant direct effect of CDO existence on digital innovation. Instead, our results show that the effect of CDO existence on digital innovation depends on the TMT's digital knowledge (see Model 1 and 2).

We further test H4, stating that the positive impact of the interplay between TMT digital knowledge and an integrative CEO, and respectively, CDO existence, on digital innovation is less (more) pronounced under a strong (flat) hierarchical structure in Model 5 (Model 6). For the effect of the interaction term between TMT digital knowledge and an integrative CEO on digital innovation, Model 5 shows an insignificant effect ($p > .10$), while Model 6 shows a significantly positive effect ($p < .10$). To test the statistical significance of the differences in the coefficients of these interaction terms in Model 5 and Model 6, we conduct a Chow test. The Chow test shows that the interaction effects for TMT digital knowledge and an integrative CEO are not significantly different in Model 5 and Model 6 (Chi^2: 0.40, $p > .10$). For the effect of the interaction term between TMT digital knowledge and CDO existence on digital innovation, Model 5 shows an insignificant effect ($p > .10$), while Model 6 shows a significantly positive effect ($p < .01$). For the interaction effects of TMT digital knowledge and CDO existence, the Chow test indicates that the effects are indeed significantly different in Model 5 and Model 6 (Chi^2: 4.03, $p < .05$). Specifically, under a flat hierarchical structure, one additional top manager with digital knowledge under CDO existence is associated with an average increase of 32.7% in digital innovation compared to an average increase in digital innovation of 4.6% under a strong hierarchical structure. These results partly support H4 by indicating a dependency of the interaction effect between TMT digital knowledge and CDO existence on the hierarchical structure in the TMT. Taken together, our results, based on fixed-effects regression models, support H1, H2, H3, while we only find partly support for H4 with regard to the interaction between TMT digital knowledge and CDO existence.

Table 3
Cross-sectional correlation matrix of regression variables.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)
(1) Digital innovation[a]	1.00																								
(2) TMT digital knowledge[b]	0.36	1.00																							
(3) Integrative CEO[c]	0.00	−0.05	1.00																						
(4) CDO existence	0.07	0.17	0.07	1.00																					
(5) CEO educational level	0.07	0.09	−0.05	−0.06	1.00																				
(6) CEO equity-based comp.[d]	0.11	0.16	−0.04	0.09	0.05	1.00																			
(7) CEO age[a]	−0.05	0.01	0.15	−0.01	0.03	0.00	1.00																		
(8) CEO tenure[a]	−0.02	−0.03	0.40	−0.04	0.00	−0.02	0.26	1.00																	
(9) CEO duality	0.14	0.16	0.03	−0.09	0.05	0.01	0.22	0.22	1.00																
(10) CINNO existence	0.02	0.10	−0.04	−0.02	−0.06	0.03	−0.03	0.00	0.03	1.00															
(11) TMT horizontal interdep.	−0.02	0.02	0.05	−0.02	0.00	0.00	−0.01	0.05	0.02	0.06	1.00														
(12) TMT educational level	0.05	0.13	−0.15	−0.04	0.50	0.07	−0.01	−0.04	0.02	−0.01	−0.02	1.00													
(13) TMT age[a]	−0.03	−0.05	0.24	−0.07	0.02	−0.04	0.45	0.12	0.12	−0.02	0.03	−0.10	1.00												
(14) TMT size[a,f]	0.27	0.53	−0.07	0.17	0.07	0.18	−0.01	−0.08	0.09	0.15	−0.33	0.13	−0.11	1.00											
(15) Board diversity[d]	0.05	0.18	0.01	0.13	−0.08	0.08	0.05	−0.05	0.10	0.07	−0.07	−0.06	0.09	0.29	1.00										
(16) Board independence[d]	0.08	0.08	−0.21	0.03	0.09	−0.03	−0.17	−0.67	−0.12	0.00	−0.08	0.07	−0.04	0.08	0.08	1.00									
(17) Board size[a,f]	0.26	0.39	−0.07	0.08	0.03	0.14	−0.04	−0.16	0.08	0.11	−0.07	0.04	0.05	0.45	0.29	0.21	1.00								
(18) Institutional ownership[d]	−0.15	−0.16	−0.08	−0.05	0.01	−0.05	−0.04	0.00	−0.14	−0.06	−0.03	0.03	−0.15	−0.20	−0.14	0.00	−0.29	1.00							
(19) Firm size[a,f]	0.41	0.41	−0.01	0.08	0.03	0.20	0.08	−0.08	0.21	0.06	−0.10	−0.06	0.17	0.54	0.27	0.11	0.57	−0.42	1.00						
(20) Capital expenditures[e]	−0.01	−0.01	0.03	−0.05	0.00	−0.02	−0.08	0.05	−0.04	0.01	−0.05	−0.04	0.07	0.02	−0.05	−0.06	0.04	−0.04	0.08	1.00					
(21) R&D intensity[f]	0.06	0.08	−0.06	−0.06	0.18	0.05	0.00	0.02	−0.01	0.04	0.01	0.39	−0.14	0.15	−0.04	−0.06	−0.07	0.06	−0.16	−0.09	1.00				
(22) Tobin's Q[e]	−0.06	−0.05	0.05	0.03	0.09	0.04	−0.06	0.09	−0.02	0.04	0.11	0.15	−0.07	−0.04	−0.01	−0.09	−0.18	−0.10	−0.22	0.08	0.28	1.00			
(23) Capital intensity[e]	−0.11	0.00	0.06	−0.03	0.02	−0.02	0.02	0.00	0.00	−0.02	−0.05	−0.05	0.22	−0.04	0.05	0.06	0.16	−0.03	0.14	0.55	−0.27	−0.18	1.00		
(24) Return on assets[e]	0.00	−0.01	0.07	0.00	0.00	0.06	0.02	0.04	0.07	0.02	0.05	−0.01	0.04	−0.05	0.01	−0.02	−0.06	−0.19	0.02	0.10	0.01	0.48	−0.07	1.00	
(25) Leverage[e]	−0.03	0.02	−0.09	0.02	−0.07	0.04	−0.04	−0.08	0.02	0.03	0.00	−0.05	−0.04	0.11	0.14	0.04	0.17	0.01	0.15	−0.17	−0.09	−0.13	−0.03	−0.16	1.00

a) Log-transformed. b) Mean-centered. c) Standardized. d) Measured in percent. e) Winsorized at 0.01 and 0.99 levels. f) Winsorized at 0.03 and 0.97 levels. Notes: Digital innovation captures the average digital patent filings in t+1 and t+2; all other variables measured in t. The correlations are based on 2413 firm-year observations of 305 firms.

Table 4
Firm fixed effects models estimating the influence on digital innovation.

Model	1	2	3	4	5	6
DV	Digital innovation					
Sample	Total	Total	Total	Total	Strong hierarchy	Flat hierarchy
TMT digital knowledge	0.053**	0.052**	0.041	0.041*	0.045	0.017
	(2.112)	(2.116)	(1.637)	(1.677)	(1.246)	(0.492)
TMT digital knowledge * Integrative CEO		0.037**		0.033*	0.022	0.044*
		(2.135)		(1.887)	(1.039)	(1.720)
TMT digital knowledge * CDO existence			0.141**	0.127**	0.000	0.265***
			(2.298)	(2.053)	(0.003)	(3.246)
Integrative CEO	0.010	0.014	0.008	0.012	0.025	0.022
	(0.524)	(0.748)	(0.439)	(0.643)	(1.137)	(0.772)
CDO existence	0.087	0.074	−0.039	−0.039	0.050	−0.144
	(1.009)	(0.865)	(-0.494)	(-0.492)	(0.507)	(-1.009)
CEO educational level	−0.044*	−0.043*	−0.043*	−0.042*	−0.056	−0.029
	(-1.849)	(-1.796)	(-1.791)	(-1.751)	(-1.462)	(-1.034)
CEO equity compensation	−0.002	0.001	−0.008	−0.005	0.046	−0.043
	(-0.048)	(0.016)	(-0.192)	(-0.123)	(0.723)	(-0.794)
CEO age	−0.698***	−0.683***	−0.677***	−0.665***	−0.843**	−0.557*
	(-2.731)	(-2.716)	(-2.678)	(-2.667)	(-2.496)	(-1.830)
CEO tenure	−0.003	0.000	−0.007	−0.004	−0.022	0.002
	(-0.123)	(-0.019)	(-0.277)	(-0.170)	(-0.705)	(0.068)
Duality	0.058	0.054	0.056	0.053	0.067	−0.007
	(1.251)	(1.184)	(1.211)	(1.154)	(1.111)	(-0.094)
CINNO existence	0.040	0.039	0.045	0.044	−0.055	0.203
	(0.464)	(0.465)	(0.523)	(0.520)	(-0.628)	(1.341)
TMT horizontal interdependence	0.013	0.021	0.015	0.022	0.096	−0.022
	(0.215)	(0.342)	(0.251)	(0.361)	(0.606)	(-0.338)
TMT educational level	−0.040	−0.046	−0.043	−0.048	−0.001	−0.078
	(-0.759)	(-0.865)	(-0.823)	(-0.912)	(-0.019)	(-1.101)
TMT average age	0.302	0.355	0.314	0.361	1.137**	−0.671
	(0.665)	(0.799)	(0.692)	(0.809)	(2.051)	(-1.054)
TMT size	−0.142**	−0.137*	−0.142**	−0.138*	−0.007	−0.240***
	(-1.994)	(-1.947)	(-2.006)	(-1.962)	(-0.053)	(-2.785)
Board diversity	0.084	0.085	0.061	0.065	0.004	0.281
	(0.389)	(0.393)	(0.288)	(0.302)	(0.014)	(0.884)
Board independence	−0.098	−0.087	−0.106	−0.095	−0.187*	−0.006
	(-1.249)	(-1.113)	(-1.370)	(-1.234)	(-1.837)	(-0.054)
Board size	−0.113	−0.111	−0.105	−0.104	−0.023	−0.113
	(-0.938)	(-0.908)	(-0.870)	(-0.849)	(-0.132)	(-0.690)
Institutional ownership	−0.007	0.004	−0.004	0.006	−0.092	0.123
	(-0.051)	(0.027)	(-0.027)	(0.040)	(-0.440)	(0.772)
Net sales	0.159***	0.162***	0.158***	0.160***	0.156**	0.154**
	(3.294)	(3.353)	(3.279)	(3.331)	(2.422)	(2.185)
Capital expenditures	0.389	0.308	0.335	0.268	0.957	−0.088
	(0.800)	(0.649)	(0.685)	(0.561)	(1.119)	(-0.194)
R&D intensity	−0.584	−0.540	−0.595	−0.555	−0.148	−0.984
	(-1.048)	(-0.995)	(-1.068)	(-1.020)	(-0.205)	(-1.123)
Tobin's Q	0.015	0.017	0.014	0.016	0.029	0.010
	(1.103)	(1.253)	(1.013)	(1.155)	(1.299)	(0.449)
Capital intensity	0.084	0.092	0.085	0.092	0.064	0.086
	(0.965)	(1.073)	(0.971)	(1.066)	(0.493)	(0.725)
Return on assets	−0.177	−0.177	−0.168	−0.168	−0.010	−0.330*
	(-1.107)	(-1.109)	(-1.041)	(-1.049)	(-0.049)	(-1.694)
Leverage	−0.111	−0.119	−0.097	−0.106	−0.086	0.033
	(-0.869)	(-0.933)	(-0.758)	(-0.825)	(-0.379)	(0.192)
Firm- and year-fixed effects	yes	yes	yes	yes	yes	yes
R^2	0.050	0.055	0.056	0.059	0.094	0.091
F value	2.76***	2.90***	2.90***	3.00***	1.63**	2.35***
Obs. (firms)	2413 (305)	2413 (305)	2413 (305)	2413 (305)	1207 (262)	1206 (253)

*p < .10; **p < .05; ***p < .01. Robust standard errors clustered at the firm-level. T-values in parentheses. Digital innovation is calculated as the natural logarithm of one plus the average digital patents filed in t+1 and t+2. Effects are estimated by using fixed effects regression models.

5.3. Robustness tests

To test the robustness of our results, we conducted several robustness tests. First, we run the set of fixed effects regressions in three alternative samples. Specifically, we restrict the sample to companies (1) that were listed for at least five years in the S&P900 in our

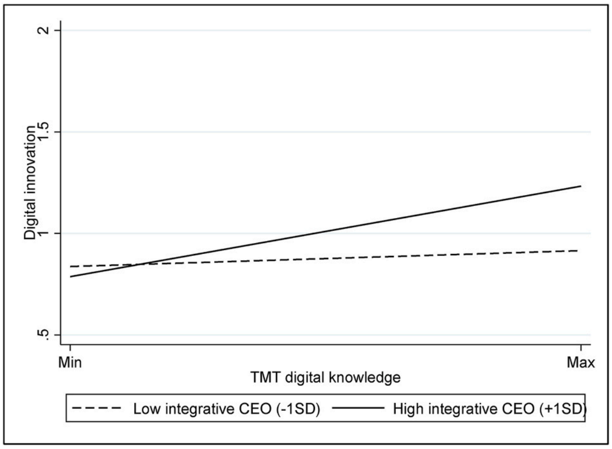

Fig. 2. Interaction of TMT digital knowledge and integrative CEO on digital innovation.

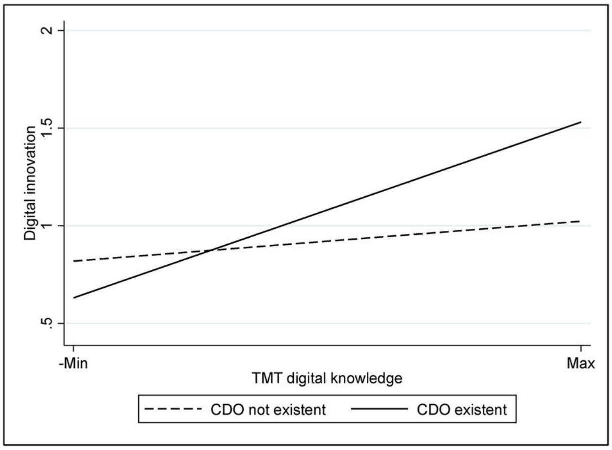

Fig. 3. Interaction of TMT digital knowledge and CDO existence on digital innovation.

observation period (Fu et al., 2020); (2) that were actually listed in the S&P900 in the year of observation, and (3) in another test, we only consider firms that were constituents of the S&P900 in the first year of our observation period (i.e., 2005). Our results remain robust in all samples. Second, we test an alternative measure of our dependent variable *digital innovation*. While our previous proxy considers patent filings independently of their granting status (e.g., also including patent filings that could be rejected), we exclusively focus on granted patents. The results also support our findings. Third, we test the robustness of our results with alternative measures of our independent variable *TMT digital knowledge*. We calculate the variable by counting the number of years top managers have worked in digital technology-related positions or industries instead of counting the number of top managers, and also calculate the variable as the percentage of top managers with digital knowledge in the TMT. Our results remain robust. Fourth, we test the fourth hypothesis by testing three-way interaction terms instead of splitting our sample into two sub samples. Our results remain robust.

6. Discussion and conclusion

In this study, we empirically examine the influence of TMT characteristics on digital innovation in the context of industrial firms. Thereby, we are among the first to respond to the calls for more research on the role of the TMT for digital innovation (Kohli and Melville, 2019; Singh et al., 2020; Volberda et al., 2021). Our results show that, on average, TMT digital knowledge is positively associated with future digital innovation. We further find that a more integrative CEO and the presence of a CDO amplifies the positive influence of TMT digital knowledge on digital innovation. Finally, our results highlight that considering the hierarchical structure in the TMT as a contextual factor for the stimulation of behavioral integration can be important. Specifically, the moderating influence of CDOs crucially depends on a flat hierarchical structure in the TMT. In contrast, we do not find that the hierarchical structure creates such obstacles for integrative CEOs in triggering behavioral integration. The latter finding could be attributed to the powerful role of CEOs in the TMT. As such, CEOs could better overcome behavioral barriers of strong hierarchical structures in their endeavors for behavioral integration.

6.1. Contributions to the literature

Our study contributes to research on TMT research in three major ways. First, our study contributes to research on the TMT's role and needed competencies for digital innovation (e.g., Hanelt et al., 2021a; Volberda et al., 2021). Specifically, case studies and conceptual research on digital innovation suggest that the top management needs to be aware of and support firm digital innovation endeavors (Hanelt et al., 2021a; Kohli and Melville, 2019; Wrede et al., 2020), but remain unclear in the specific characteristics needed in the TMT. Our study adds empirical evidence to this literature by outlining that firm digital innovation can particularly benefit from digital knowledge in the TMT. Thereby, our study also informs the debate on whether rather general managerial or digital competencies are needed for leadership in the digital era (Furr et al., 2019; Volberda et al., 2021). Specifically, we theorize on emerging role requirements for the TMT and suggest that digital innovation elevates the role of digital knowledge from one of functional importance to one of more general importance. This empirically supports the notions in recent conceptual works on digital transformation that digital technology-focused management styles are becoming increasingly important (Dery et al., 2017; Hanelt et al., 2021a).

Second, our work complements existing literature on TMT behavioral integration (e.g., Buyl et al., 2011; Simsek et al., 2005) by exploring how triggering behavioral integration takes place at internal TMT interfaces in the context of digital innovation. Here, we substantiate existing research (Buyl et al., 2011; Georgakakis et al., 2017) by outlining that integrative CEOs also have a vital role for behavioral integration under the specific peculiarities of digital innovation. Moreover, while prior literature mainly focuses on the CEO as an integrative force in the TMT (e.g., Buyl et al., 2011; Georgakakis et al., 2017), we extend this literature by highlighting how other specific TMT roles can also be highly beneficial for triggering behavioral integration in the TMT. While we focused on CDOs and the behavioral integration of digital knowledge, our findings might also be relevant for other TMT roles dedicated to specific phenomena such as sustainability (e.g., chief sustainability officer, Fu et al., 2020). In the case of such specific TMT roles, we highlight the TMT hierarchical structure as a decisive contextual factor for behavioral integration. We theorize on implicit behavioral expectations in the TMT that could unfold as barriers for integration processes under a strong hierarchical structure. In sum, our study helps to build a deeper understanding of how to promote behavioral integration at the interfaces between top managers other than the CEO.

Third, our study contributes to the emerging literature on the CDO (e.g., Kunisch et al., 2020; Singh et al., 2020). In particular, our work adds to the conceptual discussion of CDO roles. Prior literature points to the CDO as a coordinator, but also emphasizes that CDOs may act as sole innovators (Björkdahl, 2020; Reck and Fliaster, 2019; Tumbas et al., 2017). We inform this literature by showing that CDOs can have benefits as coordinators but are rather limited in their effectiveness if they are viewed solely as digital innovators in a functional sense. We also add on how the CDO role needs to be embedded in the organization to be effective. While prior research indicates that firms need to revise organization design parameters at more operative levels to provide supportive structures for the effectiveness of CDOs (Singh et al., 2020), our research complements this literature by emphasizing the relevance of flat hierarchical structures at the top level to strengthen the coordinative role of the CDO. Hence, our work provides insights into how firms may benefit from the CDO role and thereby complements CDO literature mainly focused on antecedents of CDO presence (Firk et al., 2021; Kunisch et al., 2020).

6.2. Practical implications

Our study has important implications for managerial practice due to the relevance of digital innovation in industrial firms (e.g., Svahn et al., 2017) and the debates on beneficial TMT characteristics for setting the digital innovation course (Boyden, 2017; Furr et al., 2019). First, our work outlines the benefits of digital knowledge in the TMT to accomplish the TMT's tasks in leading the firm toward digital innovation. In particular, our study suggests that digital knowledge in the TMT is beneficial for digital innovation since the TMT is better able to fulfill its emerging tasks for digital innovation, such as recognizing a digital innovation's potentials and supporting its implementation. Firms should therefore consider the relevance of digital knowledge in TMT composition processes and the design of leadership development programs (e.g., training, workshops, etc.).

Second, our work emphasizes the relevance of triggering information exchange and collaborative behavior among top managers to utilize digital knowledge. Firms should therefore consider the need for information exchange and collaborative behavior in designing structures and processes at the TMT level that facilitate the firm's digital innovation endeavors. Here, firms may assess the appropriateness of certain CEOs in triggering such information-exchange processes in the TMT as well as the need for creating novel positions in the TMT. Our study suggests that firms can benefit from the CDO position in terms of integrating TMT digital knowledge into TMT processes for digital innovation. Firms, however, should consider the hierarchical structure in conditioning the effectiveness of the integration activities triggered by TMT roles. Under strong hierarchical structures, TMT roles can be ineffective in facilitating information exchange and collaboration within the TMT due to behavioral barriers for other top managers to engage in such information exchange and collaboration. Taken together, firms should assess TMT competencies, existing roles, and structural conditions when preparing to embrace digital innovation.

Finally, our practical implications should be interpreted in light of the unforeseen challenges arising with the COVID-19 pandemic. First, this pandemic has spurred firms into taking actions for digital innovation (e.g., by providing platforms and technical infrastructures for home offices and more digital customer engagement) and has thus created more awareness of the need for digital innovation in industrial firms. This increasing awareness may help firms in seeing the need for digital knowledge in the TMT and increase the willingness to integrate this knowledge. Second, however, the pandemic requires firms to cope with the physical distances that have occurred due to the physical separation of workplaces. Managers and employees have been challenged to interact and collaborate in the digital work environment, as communication processes now need to be more explicit than in face-to-face meetings. This, in turn, creates huge challenges for the behavioral integration processes in the TMT. To prevent the occurrence of separated silos, specific TMT roles, such as the CDO, may become even more important in establishing interfaces for information exchange to overcome these physical barriers (Juneja and Sukharevsky, 2020). Thus, our results regarding the crucial role of behavioral integration should be considered in the heated discussions about digital work environments that likely outlive the COVID-19 pandemic.

6.3. Limitations and future research

Our study has some limitations worth noting. First, we focus on digital innovation by using digital patent filings. Patents present an established proxy for innovation in industrial firms characterized by a high patent intensity (e.g., Ahuja and Katila, 2001; Balsmeier et al., 2017; Custódio et al., 2019). However, the focus on patents does not allow us to make explicit statements on the digitally enabled transformation of the industrial firms' business models, which may follow on from digital innovation (Nambisan et al., 2017). It would be interesting for future research to examine which kinds of TMT knowledge and TMT roles might affect the translation of digital innovation into changes in industrial firms' business models. In addition, future research could examine how TMT digital knowledge specifically translates into firm digital innovation (e.g., for which concrete decisions and process steps) and it could also examine the role of TMT digital knowledge in the context of external innovation-related relationships (e.g., open innovation, see Chesbrough, 2003).

Second, we proxy for the TMT's digital knowledge via the experience that managers have collected in digital technology-related work positions or industries. While research often uses work experience as a proxy for the knowledge of top managers (e.g., Buyl et al., 2011; Georgakakis et al., 2017; van Peteghem et al., 2019), future research could consider further sources of knowledge creation in measuring the TMT's digital knowledge. For example, future research could account for the technological affinity that is present in the area in which the workplace is located to capture digital knowledge-creation mechanisms that take place outside of work. In addition, future research could use more explicit measures of digital knowledge by, for example, using survey-based methods, and it could also examine further TMT characteristics that may also be relevant in driving the firm's digital innovation endeavors (e.g., personality traits, such as openness).

Third, we investigate the emerging role of the CDO. While we find that the diffusion of CDOs is comparable to that found in other studies in the final years of our panel (Fu et al., 2020), we acknowledge that there may be a limitation in terms of generalizing the results due to the low number of CDO occurrences. We therefore encourage future research to further examine the consequences of the CDO role by aiming for even larger datasets. Here, future research could also explore the various facets of the CDO role that go beyond coordinative tasks for strengthening collaboration. For example, future research could focus on the effects of CDOs in facilitating customer engagement that relate to a more externally focused role closer to marketing, which is more likely to be seen in non-manufacturing industries (Horlacher and Hess, 2016; Tumbas et al., 2018).

Fourth, we acknowledge that the decision to add managers with digital knowledge to the TMT is not exogenously determined. To address the resulting endogeneity problems, we used firm fixed effects regressions and forwarded our dependent variable of digital innovation. Moreover, we focused on industrial firms, as this is a more homogenous group of firms that is challenged by similar industry developments. However, as with any other study lacking exogenous variation, correlation or causation is up for debate. Hence, we believe that it could also be fruitful to examine the firm characteristics that drive the decision to add digital knowledge to the TMT. For example, from an upper echelon perspective, it may be worth exploring the experiences and knowledge of the board, CEO, and TMT that could lead to increasing TMT digital knowledge.

6.4. Conclusion

We provide insights into beneficial TMT characteristics for digital innovation. Our study shows that digital knowledge in the TMT is positively associated with digital innovation, on average. We also find that firms can benefit from integrative CEOs and the existence of a CDO in utilizing the TMT digital knowledge for digital innovation. In benefiting from the CDO as a TMT integrator, our study outlines the relevance of a flat hierarchical structure. Taken together, our work implies that TMT digital knowledge, even in the industrial context, is becoming increasingly relevant and firms may need to assess their TMT roles and structures to embrace digital innovation.

Author statement

Sebastian Firk: Conceptualization, Methodology, Software, Investigation, Writing - original draft; Writing - review & editing. **Yannik Gehrke:** Conceptualization, Methodology, Data Curation, Software, Investigation, Writing - original draft; Writing - review & editing. **Andre Hanelt:** Conceptualization, Writing - original draft; Writing - review & editing. **Michael Wolff:** Conceptualization; Resources, Writing - original draft; Writing - review & editing.

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Appendix

Table A1
Data sources and variable descriptions

Variable	Description & Calculation	Data source
Digital innovation	Calculated as one plus the natural logarithm of the average digital patent filings in year t+1 and t+2. Patent filings are defined as digital, if they are classified in technological classes that relate to digital technologies according to the USPC scheme. Specifically, we consider the following USPC classes as related to digital technologies: 178, 333, 340, 342, 343, 358, 367, 370, 375, 379, 385, 455, 341, 380, 382, 395, 700, 701, 702, 704, 705, 706, 707, 708, 709, 710, 712, 713, 714, 345, 347, 360, 365, 369, 711, 715, 716, 717, 718, 719, 720, 725, 726.	USPTO
TMT digital knowledge	Measured as the number of top managers who possess experiences in digital technology-related positions or, for at least three years, in digital technology-related industries. The final variable is mean-centered.	BoardEx
Integrative CEO	Measured by standardizing and averaging the (1) the pairwise overlap in tenure between the CEO and the other TMT members and (2) the functional diversity in prior employments of the CEO.	BoardEx
CDO existence	Dummy variable equaling one if there is a CDO position, otherwise zero.	BoardEx & manual search
TMT hierarchical structure	Dummy variable equaling one if there is a strong hierarchical structure in the TMT, otherwise zero. The calculation is based on the median value of an index composed of (1) the vertical interdependence in the TMT (i.e., the number of hierarchical levels in the TMT and whether there is a COO) and (2) the coefficient of variation in the short-term pay among the TMT.	BoardEx & ExecuComp
CEO educational level	Coded as one for no academic degree, two for a Bachelor's degree, three for a Master's degree, four for an MBA degree, and five for a PhD degree or equivalent.	BoardEx
CEO equity compensation	Calculated as CEOs' restricted shares and stock option value divided by CEOs' total compensation.	ExecuComp
CEO age	Measured as the natural logarithm of the number of CEO's years.	ExecuComp
CEO tenure	Measured as the natural logarithm of the number of CEO's tenure.	ExecuComp
CEO duality	Dummy variable equaling one if the CEO is also the chairman of the board.	BoardEx
CINNO existence	Dummy variable equaling one if there is a chief innovation officer in the firm, otherwise zero.	BoardEx
TMT horizontal interdependence	Calculated by standardizing and averaging (1) a dummy variable indicating whether the TMT was based entirely on functional posts and (2) the number of functional roles in the TMT.	BoardEx
TMT educational level	Calculated as the average of the TMT's educational level, which is coded analogous to CEO educational level.	BoardEx
TMT age	Measured as the natural logarithm of the average number of years of each top manager.	BoardEx
TMT size	Measured as the natural logarithm of the number of top managers in the TMT.	BoardEx
Board diversity	Measured as the percentage of women under the non-executive directors.	BoardEx
Board independence	Measured as the percentage of outside directors who are not appointed by the CEO.	BoardEx
Board size	Measured as the natural logarithm of the number of non-executive directors.	BoardEx
Institutional ownership	Calculated as the sum of percentages hold by institutional owners with at least one percent of voting shares.	ThomsonOne
Firm size	Calculated as the natural logarithm of net sales.	Datastream
Capital expenditures	Calculated as capital expenditures divided by net sales.	Datastream
R&D intensity	Calculated as the R&D expenditures divided by net sales.	Datastream
Tobin's Q	Calculated as the sum of market capitalization and total assets subtracted by total shareholder's equity divided by total assets.	Datastream
Capital intensity	Calculated as property, plant, and equipment (gross) divided by total assets.	Datastream
Return on assets	Calculated as operating income after taxes divided by total assets.	Datastream
Leverage	Calculated as short-term debt divided by total assets.	Datastream

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