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Research

Digital transformation and Schumpeterian growth: inter-rationality in open innovation dynamics and finance

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Abstract
The ability to innovate is one of the most important factors causing economic progress, managing to improve competitive advantage for organizations, and helping to grow the GDP in general. This particular study analyzes the effects of digital transformation in conjunction with the theory of Schumpeterian, growth, and open innovation patterns regarding the innovation output, while paying special attention to inter-rationality as a moderator. However, although their importance is given fore, these factors especially from the empirical perspective have not been explored much in this specific combination. Primary data was collected from $n = 300$ respondents who were innovation managers, R&D and product development directors, chief technology officers, and other senior executives, respectively. The data was then analyzed using SEM-PLS technique. The results validate the assertion that digital transformation Schumpeterian growth and open innovation dynamics are strong predictors of innovation output. In particular, it is observed that transformation in the use of digital technology contributes to the impacts estimation of output innovations ($\beta = 0.371$, $p < 0.001$) and thus, an organization that integrates advanced forms of digital technology, is likely to achieve high levels of innovation. It is found that Schumpeterian growth has a positive effect on the innovation output as well ($\beta = 0.395$, $p < 0.001$), another entrepreneurial activity encompassed in this theory being unceasing development. Open innovation dynamics also increase the innovation output ($\beta = 0.409$, $p < 0.001$), which emphasizes the strategy of internal and external cooperation. Furthermore, inter-rationality acts as a significant moderator in the relations of these variables with innovation output, high interdisciplinary and cross-functional teamwork increasing these interactions.
This study gives useful information to managers, researchers and policy makers regarding the need to encourage the use of digital technologies for enhancing entrepreneurial, efforts and enabling external collaborations. These results underscore the critical role of integrating advanced digital tranformation, fostering entrepreneurial activity, and leveraging external collaborations to enhance innovation capabilities. Managers are encouraged to invest in digital tools, nurture a culture of cross-functional collaboration, and adopt open innovation strategies to maximize organizational performance. Policymakers can use these insights to design frameworks that support innovation-driven economic development.

Keywords Innovation output · Digital transformation · Schumpeterian growth · Open innovation dynamics · Inter-rationality · Technological adoption · Organizational competitiveness

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1 Introduction

The importance of innovation cannot be overlooked as it has become one of the main factors responsible for the global economic growth and alteration of the competitive environment within industries and countries [1]. According to the World Economic Forum [2] estimates, owing to digital transformation strategies, more than 60% of the GDP would be digitized within the span of two years by 2022. Digital technologies investments have been recorded to amount to $1.3 trillion by the year 2020, reflecting a 10.4% rise as compared to that of 2019 [3]. There has been an increase in the application of geographies of knowledge within firms as well, since 78% of large companies practice some form of open innovation [1, 4]. Entrepreneurship activities have also increased, with new business establishments growing by 7% around the globe in 2019, based on Global Entrepreneurship Monitor [5].

The effects and difficulties concerning innovation across regions tend to be different. About 40% of firms in the US claim to have increased R&D due to digital transformation that has fueled innovation. The same Europe has set aside €750 billion for innovation enhancing digital and green transitions. In spite of these advancements, the two regions still face challenges like lack of adequate cross disciplinary teamwork or poorly applied open innovation strategies. For illustration, partnerships between firms and universities frequently break down as a result of the differences in timelines, goals and success measures [6, 7], thereby constraining the use of knowledge sourced externally [4].

The push for the use of digital transformation and innovation in the South Asian region is on the increase, with the country of India at the forefront, making a $1.2 billion investment in AI in the year 2020 [8]. Albeit this, there are still some constraints such as poor digital infrastructure development and minimal R&D investment. Although we can observe growth with those investments, it is still an issue how to maintain and grow innovation outcomes.

It is a recent view from the existing literature that the integration of digital transformation, Schumpeterian evolution and dynamics of open innovation takes the center stage in building workable and sustainable innovation ecosystems [1, 4, 9–12]. The effective use of digital transformation strategies are those that arm organizations with tools such as AI, IoT, Blockchain among others and enhance the organization's processes [1, 4, 9–12].Such advanced technology changes the way of doing business by promoting operational efficiencies, better engagement with customers and exciting new business concepts. However, while there is abundant theoretical justification of their adoption, very little research has been done concerning this towards innovation productivity [13–17].

In the Schumpeterian economic theory growth, creative destruction plays a central role in entrepreneurship and innovation as the main driving forces of economic development [1, 18, 19]. In order to be able to advocate any economically sustainable policy, it is vital to comprehend how entrepreneurial activity and innovative level respectively influence the amount of innovation output [20, 21]

The dynamics of open innovation emphasize leveraging external knowledge through universities, research organizations, and other entities [4]. Establishing such collaborations enhances a company's ability to innovate. However, the success of these partnerships often depends on the level of inter-rationality within the organizations involved [10, 22, 23]. Inter-rationality, which should be understood as cross-functional and cross-disciplinary teamwork, plays a crucial role in driving creative and comprehensive solutions [10, 22, 23]. Moreover, it serves as a moderating factor in the relationship between digital transformation, Schumpeterian growth, open innovation, and innovation output.This study aims to bridge existing gaps by examining the relationship between digital transformation, Schumpeterian growth, and open innovation dynamics on one side, and innovation output on the other, while considering the moderating role of inter-rationality. Drawing on data from 300 informants—including innovation managers, R&D directors, chief technology officers, and other senior executives—this research provides an in-depth understanding of innovation within the dialectics of contemporary technologies and their economic impact.

Despite extensive research on digital transformation, Schumpeterian growth, and open innovation dynamics, a significant gap remains in understanding their combined impact on innovation output within a moderated framework. Much of the existing literature treats these elements in isolation, rather than exploring how inter-rationality—cooperation across functions and disciplines—moderates their effects on innovation outcomes. While numerous studies emphasize the importance of open innovation, particularly the role of external partnerships and the integration of external knowledge, few have examined its practical implementation and the influence of technology and entrepreneurship on innovation performance. This lack of empirical findings presents a critical gap, limiting the ability to bridge theoretical advancements with practical applications in the field.

This study addresses this gap by examining the underexplored role of inter-rationality as a moderating factor in the relationship between these constructs. Unlike previous research, which often focuses on theoretical arguments or narrow

empirical models, this study utilizes primary data from senior executives across multiple industries to empirically assess the integrated effects of these factors on innovation output.

The findings highlight not only the individual contributions of digital transformation, Schumpeterian growth, and open innovation but also the amplified impact that emerges when inter-rationality is high. By addressing this overlooked aspect, the study provides fresh insights that enhance the understanding of innovation management in contemporary organizations.The analysis indicates that factors such as digital transformation, Schumpeterian growth and open innovation dynamics are antecedents of innovation output. Digital transformation helps innovate organization ($\beta = 0.371$, $p < 0.001$) thereby innovation output increases due to the implementation of sophisticated digital technologies. In the same fashion, Schumpeterian growth ($\beta = 0.395$, $p < 0.001$) and open innovation dynamics ($\beta = 0.409$, $p < 0.001$) also have a positive effect on innovation output. In addition, inter-rationality also serves to increase the effect of these factors through facilitating very high interdisciplinary and cross functional unit connections. Therefore, all six hypotheses hold true as it's shown their combinatorial approach is effective in enhancing the output of innovation. In particular, the focus is on the structure of open innovation that enables the use of external resources and cooperation between organizations, and the results of the study support that positively affects the innovation performance.

On the one hand, while the previous studies focused on one or two of the factors, the present work is able to provide a new insight concerning the three factors, which is an added contribution to literature. Along with that it has managerial and policy implications that stress the need for management structures that integrate the use of new technologies, the promotion of entrepreneurial initiatives, use of external sources of innovation and internal interactive teamwork for the purposes of innovation. The ability to cope with these aspects can be of paramount importance for building the innovative potential of organizations and economic growth in general little focused on to date [1, 4].

The study's implications are twofold. From a theoretical perspective, it advances the literature on innovation management by synthesizing digital transformation, Schumpeterian growth, and open innovation dynamics into a cohesive framework. This addresses prior limitations in siloed research and highlights the moderating role of inter-rationality in driving innovation. Practically, the findings offer actionable insights for managers and policymakers. Organizations are encouraged to invest in digital technologies and foster collaborative cultures that leverage external knowledge while prioritizing internal coordination. Policymakers can design initiatives that support cross-sector partnerships and digital infrastructure development, ensuring sustainable innovation ecosystems. These contributions make the study highly relevant for academics, industry leaders, and government stakeholders alike.

2 Literature review

2.1 Digital transformation and innovation

Digital transformation is an ongoing socio-structural change that involves the strategic integration of digital technologies to reconfigure business models, enhance innovation capabilities, and sustain competitive advantage [24, 25]. In the context of Schumpeterian innovation, digital transformation can be defined as the systematic integration of advanced digital technologies that enable firms to reconfigure their business models, enhance entrepreneurial agility, and accelerate disruptive innovation [24, 25]. Digital transformation does not merely optimize existing processes but fosters radical industry shifts, aligning with Schumpeter's notion of creative destruction, where new technologies displace older market structures to drive economic progress. It extends beyond technological adoption by fostering organizational agility, enabling entrepreneurial innovation, and reshaping industry dynamics through creative destruction. Digital transformation is the process of adopting and integrating technologies such as AI, the IoT or block chain into the internal processes of organizations [9, 13, 26, 27]. Such technologies are capable of transforming business processes, improving productivity, and promoting creativity. According to Jiang and Wang [27], Cheng [28], Ren et al. [29], digital transformation is also beneficial to business by fostering innovation, as firms that employ digital technologies are able to design and produce new goods and services with ease. Accordingly, Nambisan et al. [30] argue that the formulation of a detailed digital business strategy is necessary to attain superiority over competitors through innovation. Nevertheless, Khin and Ho [31] as well as other authors present the results of empirical investigations that reveal a lack of sufficient research into how digital transformation directly affects the innovation outcomes that can be measured in quantitative terms.

2.2 Schumpeterian growth and innovation

Ziemnowicz [21] advanced the theory of economic development by introducing the term innovation as a register of economic growth taking place through creative destruction [18, 32] Schumpeterian concern for growth looks at the disruptive effects of entrepreneurial activities and continuous innovation in existing market structures creating new markets. Ács et al. [20] also expands the propositions of Schumpeterian growth by connecting the entrepreneurial and innovation activities within industries to observable innovations. In spite of the strong theoretic assumptions, there are very few empirical studies that explain how Schumpeterian growth manifests itself in the sustained innovative output of the organization.

2.3 Open innovation dynamics

Open innovation, a term made popular by Bertello, can be defined as the exploitation of knowledge and resources by way of cooperation with entities outside the firm. Such external collaboration helps companies to improve their innovative capacity to a great extent. A detailed examination of open innovation is presented by West and Bogers [33], West and Bogers [34], West and Gallagher [35], and its advantages for promoting innovation are discussed. Yet, Bertello et al. [1], Yun [22], Hameed et al. [36], Markovic, Koporcic [37]argues that the theoretical research that measures how much open innovation contributes to the innovation output is scant. In addition, the ways in which such engagements promote innovation have not been clearly defined.

2.4 Inter-rationality and innovation

Inter-rationality, defined as the degree of interdisciplinary and, cross-functional team collaboration, is critical for enhancing innovation, outcomes. Kanter [38] and Edmondson and Harvey [39] highlight the, importance of effective knowledge integration and, collaboration between different, disciplines for developing, innovative solutions. Yun et al. [40] argue that inter-rationality can significantly enhance the, effectiveness of digital, transformation and open innovation efforts. Despite its importance, the moderating, effect of inter-rationality on the relationship between digital, transformation, Schumpeterian growth, open, innovation dynamics, and innovation output has not been thoroughly investigated.

2.5 Theoretical framework and hypothesis development

In constructing the theoretical framework, each variable was deliberately selected to reflect the essential drivers of innovation as highlighted in prior research. Digital Transformation (DT) equips organizations with the technological infrastructure needed to redesign business models and enhance operational capabilities, fostering agility and innovation [41, 42]. Schumpeterian Growth (SG) captures the entrepreneurial dynamism and market reconfigurations necessary for disruptive innovation, consistent with Schumpeter's theory of creative destruction and expanded upon by Acs and Szerb [43]. Open Innovation Dynamics (OID) reflects the critical role of external collaborations and knowledge flows, as emphasized by Chesbrough [44] and West and Bogers [33], allowing firms to extend their innovative capacity beyond internal boundaries. Finally, Inter-rationality (IR) is introduced as a moderating force, recognizing that interdisciplinary collaboration significantly amplifies innovation outcomes by integrating diverse expertise, as stressed by Kanter [38] and Edmondson and Harvey [39]. Together, these variables provide a holistic perspective on how technological adoption, entrepreneurial action, external partnerships, and internal collaboration synergize to enhance innovation output.

This study purports a theoretic perspective which incorporates a converging digital transformation and Schumpeterian growth and open innovation dynamics concentrating on the moderating effect of inter-rationality. Literature review indicates that one theory around the relationship is not sufficient, thus this research is based on four important approaches remaining: Digital Transformation Theory which asserts that the embrace and application of digital technologies to processes within organizations fosters innovation [41, 42]. Just as with the Schumpeterian growth theories that post rate the importance of creative processes and innovations which constantly be created Chu et al. [18], Ács et al. [20], Open Innovation According to theory which offers the view of the need for firm to learn from the outside world together with existing knowledge to better its innovative capabilities Chesbrough [44] Inter-rationality Theory stresses out the need of teamwork from people of varied fields in order to achieve innovation within an organization Kanter [38, 39]. This

framework assesses how factors such as digital maturity, entrepreneurial actions, and external collaborations turn out to be of significance on innovation output. Inter rationality serves to strengthen these relationships.

This study examines the relationship between Digital Transformation (DT), Open Innovation Dynamics (OID), and Schumpeterian Growth (SG) in driving Innovation Output (IO) by integrating Dynamic Capabilities Theory (DCT) and Innovation Ecosystem Theory. DCT explains how firms develop, implement, and reconfigure their digital, entrepreneurial, and collaborative capabilities in response to evolving market conditions. Meanwhile, Innovation Ecosystem Theory highlights how external partnerships and digital infrastructure sustain long-term innovation performance. Within this framework, DT functions as an enabler, embedding digital technologies to enhance operational efficiency and knowledge processing—both essential for innovation-driven strategies. SG acts as the driver, leveraging market reconfiguration, entrepreneurial dynamism, and creative destruction to foster disruptive innovation. OID serves as a mediating force, facilitating external knowledge absorption, inter-organizational collaboration, and resource-sharing, thereby amplifying the effects of DT and SG on innovation performance. By integrating these elements, the proposed framework offers a holistic perspective: DT provides the technological foundation, SG fuels entrepreneurial dynamism, and OID ensures effective knowledge diffusion, collectively maximizing innovation output.

While previous studies have examined these constructs individually, they rarely consider their integrated effects within a moderated framework. Most importantly, the moderating role of inter-rationality—cross-functional collaboration—in enhancing innovation outcomes remains significantly underexplored. This gap limits our understanding of how digital transformation, entrepreneurial dynamism, and external collaboration synergize to drive innovation."

2.6 Hypothesis development

H1 Digital transformation positively impacts innovation output

Digital transformation refers to the integration of advanced technologies such as AI, IoT, and blockchain into organizational processes, which is said to improve operational effectiveness and foster innovation [1, 4, 7, 9, 10, 13, 18, 22, 23, 32]. This is based on Digital Transformation Theory, which claims that organizations drive innovation by first adopting and integrating digital technologies into their business processes [26, 28, 45]. Frank et al. [46] stressed the critical role of digital transformation in the generation of new goods and services, thus facilitating an increase in innovative output [24, 45, 47, 48]. As per Bharadwaj et al. [41], in order to realize competitive differentiation by means of innovation, a comprehensive digital business strategy is imperative.

Critically speaking, while these studies make it possible to analyze the studied phenomena, they also identify those which require empirical study. Frank et al. [46] considers digital transformation to be an engine of innovation, however, it is not clear how exactly digital technologies are combined within organizations to produce innovation output [10, 28, 29]. For example, the application of predictive analytics and decision support systems through data modeling, enhancing interconnectivity, and real-time data gathering using the Internet of Things (IoT), or securing transactions through blockchain technology [31]. Still, how these technologies translate into actual innovation measures, like patent applications, new product introductions, or income generation from new service offerings, is still not sufficiently addressed [31].

Bharadwaj et al. [41] argue that digital business strategies enable, firms to develop new business models and improve, operational,efficiencies. This assertion is supported by numerous case studies and anecdotal evidence [41]. However, these, strategies' effectiveness can vary significantly, across different organizational, contexts and industries. For instance, companies in the technology sector might, experience more pronounced benefits from digital transformation than those in,traditional manufacturing, where the adoption, of digital technologies could be slower and more, challenging due to legacy systems and processes [10, 27–29].

Furthermore, Khin and Ho [31] highlight the need, for empirical validation of the direct, link between digital transformation and innovation, output. While theoretical models, suggest that digital transformation, should lead to enhanced, innovation, empirical studies often reveal a more nuanced picture [42]. Factors such as organizational readiness, employee, skill levels, and the presence of a supportive innovation, culture can significantly influence the outcomes of digital transformation initiatives.

Critically, the hypothesis also considers potential barriers, to successful digital, transformation. Resistance to change, high implementation costs, and cybersecurity, concerns are significant challenges that organizations, must navigate. These barriers can impede the, expected positive impact of digital transformation on innovation, output, suggesting that the relationship may not be straightforward and linear.

Consequently, drawing from the Digital, Transformation Theory and the respective publications of Feng et al. [13], Cheng [28], Ren et al. [29], Bharadwaj et al. [41], Vial [42], Zhao et al. [49] it is suggested as a hypothesis that *digital transformation leads to innovation output as it allows organizations to harness new technologies for greater efficiency and more innovative capabilities.* This hypothesis intends to address the concern stated by Khin and Ho [31], which provides justification and evidence for the association between digital transformation and innovation, output. Having established this relationship, the aim of the study is to examine the circumstances under which digital transformation is most capable of leading to innovation.

H2 Schumpeterian growth positively impacts innovation output

Schumpeterian Growth Theory advocated by Joseph Schumpeter in the year 1934 clearly explains how, entrepreneurship and innovation and more of it contributes to the overall growth of an economy. Schumpeter noted the, notion of 'creative, destruction,' in which a new technology or market as a business model destroys the previous one. There exists a constant this growth is important to economic progress and effective output of innovations. Jafari-Sadeghi et al. [48], Ashraf et al. [50], Hart et al. [51], persuade that as a rule, economies and structures oriented towards entrepreneurship and innovations gain much more growth and competitive advantage.

Ács et al. [20] bridges the gap introduced by Schumpeterian growth theory, by identifies the relationship between innovation activities of industries and their end result. They state that when an industry has higher entrepreneur activity, it is likely that there will be higher output in terms of innovation, new products, patents and technologies. Yet, despite the existence of a significant theoretical basis, studies that have proved such relationships in organizations are very few [18, 32, 52]. This void in the literature recommends the further study to prove these theoretical assumptions in real life situations.

A closer look at the accounts of Schumpeterian growth theory reveals also its many drawbacks. Innovation is said to be radical in character, that is its transforming effect on the existing order. But this factor alone has not been able to explain the different levels of responsiveness and preparedness of different organizations towards the disruptions that innovation causes. For instance, new entrants and—start-ups are fast and demand new ideas yet for older companies, it can be impossible to break free from the old, practiced ways and 'archaic' technologies [19, 53, 54]. Herein lies the difference of context of –industries, organizations, and any entrepreneurial—activities performed within them—innovation leading to output may be more or less profound in certain instances.

Evidently, Schumpeterian theory of economic development likewise gives primacy to the process of innovation, however, the spectrum of the concept, that is, the functional mechanisms of keeping entrepreneurial activity for systemic changes are not well defined. Factors such as assigning resources, internal culture or motive forces, or external conditions can influence i.e. operational abilities of entrepreneurship and success of any initiative [28]. Challenges in, for, example, innovation for companies situated in very conservative industries would be, on the other hand, lesser than for industries situated in freer markets, as they, too, would employ a range of different barriers.

What Ács et al. [20] pointed out were the empirical limitations advises of a more thorough methodology that takes into account sources of variation in context. High levels of innovation tend to be observed in the wake of high levels of entrepreneurial activity. However, the characteristics of such activity are not always the same, and its quality differs to a considerable extent. Every business initiative aimed at establishing a new enterprise is not necessarily associated with a radical change. Some of them will bring a steady but not revolutionary advancement capable of contributing to greater changes in the economy.

Furthermore, the concept of creative destruction implies a cyclical, process of, innovation and obsolescence. Organizations must, continuously invest in R&D and foster a, culture of innovation to maintain their competitive edge. However, the financial and, managerial, commitment required for sustained innovation can be substantial, posing, challenges for many firms, especially SMEs [37, 55]. This highlights the need, for supportive policies, and frameworks that encourage and facilitate ongoing innovation, efforts.

Hence, extending Schumpeterian growth theory as well as the contributions from Ács et al. [20], this hypothesis proposes, irrespective of industries' thickness entrepreneurial activities become rampant and innovation rates within industries become high, innovation output will be high. In analyzing this correlation, the research attempts to test the principles of Schumpeterian growth theory and explore how organizations can use promotion of entrepreneurs activities to increase their innovation metrics. This examination, however, will also take into account the moderating organizational and industry-specific variables in order to deliver a more complex interpretation of the dynamics involved.

H3 Open innovation dynamics positively impact innovation output

Open innovation, as, defined by Chesbrough and Appleyard [56], Chesbrough [44], involves collaborating with, external entities such, as universities, research, institutes, and other organizations to leverage external knowledge and resources. This approach enhances a,firm's innovative capabilities by integrating diverse, perspectives and expertise, fostering an environment conducive to breakthrough, innovations. The open innovation theory posits that external collaborations, and knowledge integration significantly, enhance a firm's ability to innovate and stay competitive.

West and Bogers [33] underscore the, benefits of, open innovation in, driving innovation, highlighting that organizations, engaging in open innovation practices can access a wider array of ideas, technologies, and markets. This, expanded access allows, firms to, combine internal and external knowledge more effectively, leading to more robust innovation, outcomes [1, 4, 18, 22]. By collaborating, with external entities, firms can mitigate the, limitations of their internal resources and, capabilities, enabling them to tackle complex, problems and develop innovative, solutions that they might not achieve independently.

Huizingh [57] emphasizes the need for empirical, research to, quantify the impact of open innovation on innovation output. Despite the theoretical, consensus on the benefits of open innovation, empirical studies that systematically, measure these effects are, limited. This gap underscores the importance of investigating how different, types of open innovation practices—such as joint research projects, innovation, competitions, and knowledge-sharing platforms—contribute to tangible innovation, outcomes.

Critically analyzing open innovation theory, reveals, several aspects. While external collaborations can enhance innovation, they also introduce, challenges such as, managing intellectual property (IP) rights, aligning goals, between diverse partners, and coordinating across organizational boundaries [58]. These challenges, necessitate robust governance structures, and clear communication, protocols to ensure that collaborations are effective and mutually beneficial.

Moreover, the effectiveness of open, innovation practices can vary, depending on the, industry and organizational context. For instance, industries with, rapid technological advancements and high R&D intensity, such as, biotechnology and information, technology, might experience more pronounced benefits from open innovation due to the dynamic, and, knowledge-intensive, nature of these sectors [59]. In contrast, industrywide slower innovation cycles or more rigid regulatory, environments might face, greater difficulties in, implementing open innovation practices effectively.

Additionally, firms must balance the benefits of, openness with, the potential risks of, over-reliance on external partners. Excessive dependence on external knowledge sources can lead to a dilution of a firm's interna, capabilities and strategic, autonomy [60]. Therefore, successful open innovation requires a strategic approach that integrates external collaborations while maintaining and enhancing internal R&D capabilities.

Building on the theoretical foundations of open, innovation and supported by, insights from Chesbrough et al. [61], West and Bogers [33], West and Bogers [34], West and Gallagher [35], this, hypothesis posits that open innovation dynamics, positively impact innovation output. By empirically, examining the relationship between external, collaborations and innovation outcomes, this study aims to provide robust evidence of the benefits of open innovation. It will also explore the, moderating factors that influence the effectiveness of open innovation, practices, such as industry characteristics and organizational capabilities, to offer a comprehensive, understanding of how firms can,leverage external knowledge to drive innovation.

H4 Inter-rationality moderates the relationship between digital transformation and innovation output, such that the relationship is stronger when inter-rationality is high

Inter-rationality, defined as the degree of, interdisciplinary and cross-functional, team collaboration, is crucial for effective, knowledge integration, and innovation. This hypothesis is grounded in Inter-rationality Theory, which posits that, collaborative efforts, across different disciplines enhance the impact of technological adoption on innovation.

Kanter [38] and Edmondson and Harvey [39] argue that, inter-rationality enhances innovation outcomes by facilitating seamless, collaboration and the integration of,diverse innovation practices. When team, from different disciplines work, together, they brin, varied perspectives and expertise, which can lead to more, comprehensive and innovative, solutions. This collaborative synergy is particularly, important, in the context of digital transformation, where the integration of advanced technologies, such as AI, IoT, and blockchain requires diverse skills and knowledge bases.

The effectiveness of digital transformation in driving innovation output is likely to, be enhanced when inter-rationality is high. Interdisciplinary teams are, better positioned to leverag, digital technologies to develop innovative solutions because they, can integrate different, viewpoints, solve complex problems more effectively, and adapt, to new

technological, advancements rapidly [9, 13, 26, 28]. For instance, a team comprising data scientists, engineers, and, marketing professionals can collaboratively develop a data-driven marketing strategy that utilizes, AI to predict customer, behaviors, thereby, creating more targeted and innovative marketing campaigns.

Moreover, high inter-rationality can help, overcome the silos that often, impede the successful implementation of digital transformation, initiatives. Organizational silos can, lead to, fragmented efforts, where different departments work in isolation, without, leveraging the potential synergies of integrated technologies. By fostering a culture, of interdisciplinary, collaboration, organizations can ensure that digital transformation efforts, are cohesive and aligned with overall innovation goals, thus maximizing the, impact on innovation output.

Empirical evidence supports the importance of inter-rationality in enhancing innovation outcomes. For example, cross-functional teams, have been shown to improve product development processes and, outcomes by integrating, diverse expertise and fostering creativity [62]. Additionally, organizations that promote inter-rationality tend to be more agile and responsive to technological changes, further, enhancing their capacity, for innovation [12, 63].

However, achieving high inter-rationality is not without challenges. It requires overcoming barriers such as differing departmental priorities, communication gaps, and resistance to, change. Effective leadership and a, supportive organizational culture are essential to promote interdisciplinary collaboration. Training programs, joint projects, and, integrated performance metrics can also facilitate the development of inter-rationality within organizations.

Therefore, based on Inter-rationality Theory and supported by the insights from Kanter [38], Edmondson and Harvey [39], this hypothesis posits, that inter-rationality, moderates the relationship between digital, transformation and innovation, output, such that the relationship is stronger when inter-rationality is high. By examining this moderate effect, the study aims to provide empirical evidence on the critical role of interdisciplinary collaboration in, enhancing the outcomes of digital transformation initiatives, offering, valuable insights for organizations seeking to boost their innovation, capabilities.

H5 Inter-rationality moderates the relationship between Schumpeterian growth and innovation output, such that the relationship is stronger when inter-rationality is high

Schumpeterian growth theory posits that entrepreneurial activities and, continuous innovation are key drivers of economic growth. Ziemnowicz [21] emphasized that, innovation leads to creative destruction, wherein new, technologies and business models, disrupt existing market structures, fostering economic development and enhancing innovation, output. However, the success, of these entrepreneurial activities can be, significantly amplified through interdisciplinary collaboration, or inter-rationality.

Inter-rationality, defined as the, degree of interdisciplinary and, cross-functional,team collaboration, plays a crucial role in, enhancing the, effectiveness of,entrepreneurial,activities and innovation efforts. Garud et al. [64] argue, that inter-rationality fosters creative, problem-solving and the development of innovative solutions by, integrating diverse knowledge and expertise. When teams from various disciplines collaborate, they, bring different perspectives and skills, which can lead to more comprehensive and innovative, outcomes.

In the context of Schumpeterian growth, highbinder-rationality means, that entrepreneurial activities are more likely to translate into tangible innovation, outputs. For instance, a startup team that includes engineers, marketers, financial, experts, and designers is better equipped to develop a well-rounded product that meets market needs, is financially viable, and is, technically feasible. This diverse expertise, enhances the team's ability to innovate and adapt to market changes, thereby increasing, the likelihood of successful innovation.

Empirical studies support the notion that interdisciplinary, collaboration enhances, innovation outcomes. For example, Edmondson and Harvey [39, 65] found that cross-boundary, teaming leads to higher levels of innovation by, facilitating the integration of, diverse knowledge bases. Similarly, Kanter [38] highlighted that, organizations that promote inter-rationality tend to be more, innovative and adaptive, as they, can leverage the strengths of different, disciplines to create novel solutions.

However, fostering inter-rationality within organizations is not, without challenges. It requires effective communication, mutual respect, and a culture that values collaboration. Organizations must overcome barriers such as departmental silos, differing priorities, and resistance to, change. Leadership plays a critical role in promoting inter-rationality by encouraging, collaboration, providing resources for, cross-functional projects, and recognizing, and rewarding team efforts.

When inter-rationality is high, entrepreneurial, activities are more effectively channeled into innovative outputs. This synergy between Schumpeterian growth, and inter-rationality means that organizations can maximize their innovation, potential by fostering interdisciplinary collaboration. For instance, entrepreneurial ventures that involve collaborative

efforts across marketing, engineering, and operations are more likely to, develop successful, and innovative products than those working in, isolation.

Therefore, building on Schumpeterian growth theory, and inter-rationality theory, this, hypothesis posits that the positive impact of entrepreneurial activities on, innovation output is, amplified by effective interdisciplinary collaboration. By examining this, moderating effect, the study, aims to provide empirical evidence on the, critical role of inter-rationality in enhancing the outcomes of entrepreneurial activities and innovation efforts., This will offer valuable insights for organizations seeking to leverage, interdisciplinary collaboration to boost, their innovation capabilities and achieve, sustainable growth.

H6 Inter-rationality moderates the relationship between open innovation dynamics and innovation output, such that the relationship is stronger when inter-rationality is high

Open innovation dynamics involve collaboration with, external entities such as universities, research institutes, and other organizations to leverage, external knowledge and resources, thereby enhancing a firm's innovative, capabilities. Chesbrough [44], West and Bogers [34] underscore the significant, benefits of such collaborations in driving, innovation. These external collaborations allow firms to, access a broader range of ideas, technologies, and expertise, which can lead to more robust innovation outcomes.

However, the effectiveness of open innovation initiatives, often hinges on the degree, of inter-rationality within the, organization. Inter-rationality, defined as the extent of interdisciplinary and cross-functional collaboration, is crucial for effectively, integrating and applying, external knowledge. Edmondson and Harvey [39] emphasize, that interdisciplinary and cross-functional collaboration is essential for translating external knowledge into innovative, outcomes. When inter-rationality is high, organizations are better equipped to, synthesize and utilize the diverse knowledge and resources acquired through open innovation practices.

In organizations with high inter-rationality, the, collaborative efforts of, teams from different disciplines enhance the ability to integrate external knowledge into, the innovation, process. For instance, a firm that, collaborates with a, university on a research project can benefit from the academic expertise and cutting-edge, research. If this firm, has high inter-rationality, its internal teams—including R&D, marketing, and operations—can work together effectively, to apply the external knowledge gained, leading to the development of innovative products or processes.

Empirical studies support the notion that interdisciplinary collaboration enhances the impact of open innovation. For, example, Dahlander and Gann [58] found that, firms that successfully integrate external knowledge through cross-functional teams tend to achieve higher innovation performance. This integration process involves not only adopting external, ideas but also adapting and refining them to fit the firm's specific context and, needs, which requires effective communication and collaboration among diverse teams.

Conversely, when inter-rationality is low, the potential benefits of, open innovation can be undermined. Organizations may struggle to integrate external, knowledge effectively due to siloed structures, poor communication, and a lack of collaborative culture. This can result in missed opportunities and suboptimal innovation outcomes, despite having access to valuable external resources.

Therefore, this hypothesis posits that the positive impact, of open innovation dynamics on innovation output is stronger when,inter-rationality is high. By, facilitating seamless collaboration across different disciplines, high inter-rationality enables organizations to, maximize the benefits of their open innovation initiatives. This hypothesis aims to empirically, test the moderating role of inter-rationality in the relationship between, open innovation dynamics and innovation output, providing insights into how, organizations can enhance, their innovation, capabilities through effective interdisciplinary collaboration.

3 Methodology

This study collected data from key informants within, organizations to explore digital transformation, Schumpeterian, growth, open, innovation dynamics, inter-rationality, and innovation output. We followed the methodology, of Ren et al. [29], Vial [42], Jafari-Sadeghi et al. [48], Li et al. [66] and collected data, from the key informants included innovation managers, R&D directors, chief technology officers, and senior executives, involved in strategic decision-making related to innovation. These respondents were, chosen because of their extensive knowledge and insights, which are crucial for providing accurate and, comprehensive information about their organization's innovation activities and,

outcomes. Previous, studies emphasize the importance of targeting senior managers and executives as respondents in innovation research. Brynjolfsson and McAfee [67] highlight that these, individuals are typically involved in strategic planning and possess a comprehensive, understanding of their organization's innovation processes and outcomes. Additionally, their insights are critical for assessing, the impact of digital transformation and open innovation dynamics on, innovation output [36, 53, 68]. The context of the study is particularly, relevant due to the rapid pace of digital transformation and the increasing importance of innovation, across various industries.

3.1 Sample and data collection procedures

Data collection involved a structured questionnaire, designed to gather both quantitative and qualitative insights. The survey featured, closed-ended questions rated on a Likert scale and open-ended questions for detailed, responses. Key informants within each organization, were targeted, and multiple distribution methods were used to maximize response rates and convenience. Personalized emails with survey links were sent to identified respondents, and an, online platform, Google Forms, facilitated, easy access and completion. Survey links were also shared via WhatsApp for quick and, convenient reach. For organizations with limited digital communication, physical visits, were conducted to administer the survey in person.

Initially, 800 potentials, respondents were contacted, resulting in 515 responses. After excluding incomplete responses, we obtained 412 usable responses in the first wave. Three months later, a second wave yielded 396 usable responses, achieving a 96% follow-up rate and an overall response rate of 49.5% (see Table 1).

3.2 Measures of focal constructs

All constructs were assessed using a, seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). The constructs measured included digital transformation, which was assessed through questions about the extent and impact of digital technologies in the organization. Schumpeterian growth was measured by evaluating innovation-driven, growth and competitive dynamics. Open innovation dynamics were evaluated by understanding collaboration patterns, external partnerships, and innovation networks. Inter-rationality was assessed through questions on inter-organizational rationality, and decision-making processes. Finally, innovation and output was measured by capturing data on new products, processes, and business model innovations.

Table 1 Demographic profile of respondents

Demographic variable	Category	Frequency (n)	Percentage (%)
Organizational role	Innovation managers	150	36.4
	R&D directors	120	29.1
	Chief technology officers	85	20.6
	Other senior executives	58	14.1
Industry sector	Manufacturing	140	34.0
	Technology	110	26.7
	Healthcare	75	18.2
	Services	65	15.8
	Other	30	7.3
Years of experience	< 5 years	80	19.4
	5–10 years	150	36.4
	11–20 years	130	31.5
	> 20 years	73	17.7
Company size	Small (< 50 employees)	100	24.2
	Medium (50–249 employees)	160	38.8
	Large (> 250 employees)	152	36.8

3.3 Pretest

Before starting the survey on a large scale, we pretested the questionnaire to ensure its quality. This technique reduces uncertainty and eliminates redundancy in survey, constructs by carefully probing them and conducting a preliminary analysis on, representative pilot data. Prior, to data collection, we refined the survey, constructs using several, techniques.

Initially, we adapted the questionnaire constructs from existing literature consulted with faculty experts in the relevant field [1, 4, 18, 22]. This adaptation involved a thorough evaluation to enhance the content validity, ensuring the items accurately conveyed the intended meanings. Once we developed satisfactory survey items, we further refined them.

We invited eighty respondents, including innovation managers, R&D directors, chief, technology officers, and senior executives, for one-on-one meetings. They provided detailed feedback on the language of the constructions. Based on their input, we made minor adjustments. This pretesting process significantly improved the content validity of the survey items, resulting in a rigorously tested scale suitable for both, practitioners and academics. The next section outlines the findings from the pilot study.

3.4 Pilot testing

To evaluate the validity of the proposed model, we pilot-tested the survey items, before large-scale data collection. This step is crucial to ensure the validity and reliability of the, constructs. Given the difficulty of gathering a large sample of working professionals, we used a convenient sample of full-time students to confirm the content validity of the survey.

Our primary goal was to verify the reliability of the survey items. We developed the online survey and distributed it via email and WhatsApp. Out of 400 respondents, we, received 300 valid responses. We analyzed this data using SmartPLS software to ensure that the constructs' reliability met acceptable standards.

The pilot testing results showed that all, constructs had satisfactory reliability, with, Cronbach's alpha values above the acceptable threshold of 0.70, and many, exceeding 0.90. Factor loadings were also greater than 0.70, with numerous items above 0.90. These results confirm the robustness of the survey items and their suitability for the main study (see Table 2).

These pilot testing results enhance the content validity of the survey and items and provide a rigorously tested scale for practitioners and, academicians. This preliminary testing ensures that the items used in the survey are reliable and, valid, setting a strong foundation, for the main, data collection phase.

3.5 Reliability and convergent validity

We rigorously tested the constructs for convergent validity, and reliability, using metrics such as Cronbach's alpha, factor loadings, and average, variance extracted (AVE) [69]. A confirmatory factor, analysis (CFA) with SmartPLS validated the survey, items. The results confirmed that all constructs were reliable, with Cronbach's alpha values above 0.70.

Table 2 presents the pilot testing results

Construct	Cronbach's Alpha	Average variance extracted (AVE)
Digital transformation	0.91	0.76
Schumpeterian growth	0.89	0.72
Open innovation dynamics	0.92	0.78
Inter-rationality	0.88	0.74
Innovation output	0.93	0.81

Table 3 Reliability and convergent validity

Construct	Cronbach's alpha	Composite reliability	AVE
DT	0.855	0.895	0.631
IO	0.848	0.891	0.621
IR	0.785	0.850	0.533
OID	0.795	0.859	0.551
SG	0.836	0.883	0.603

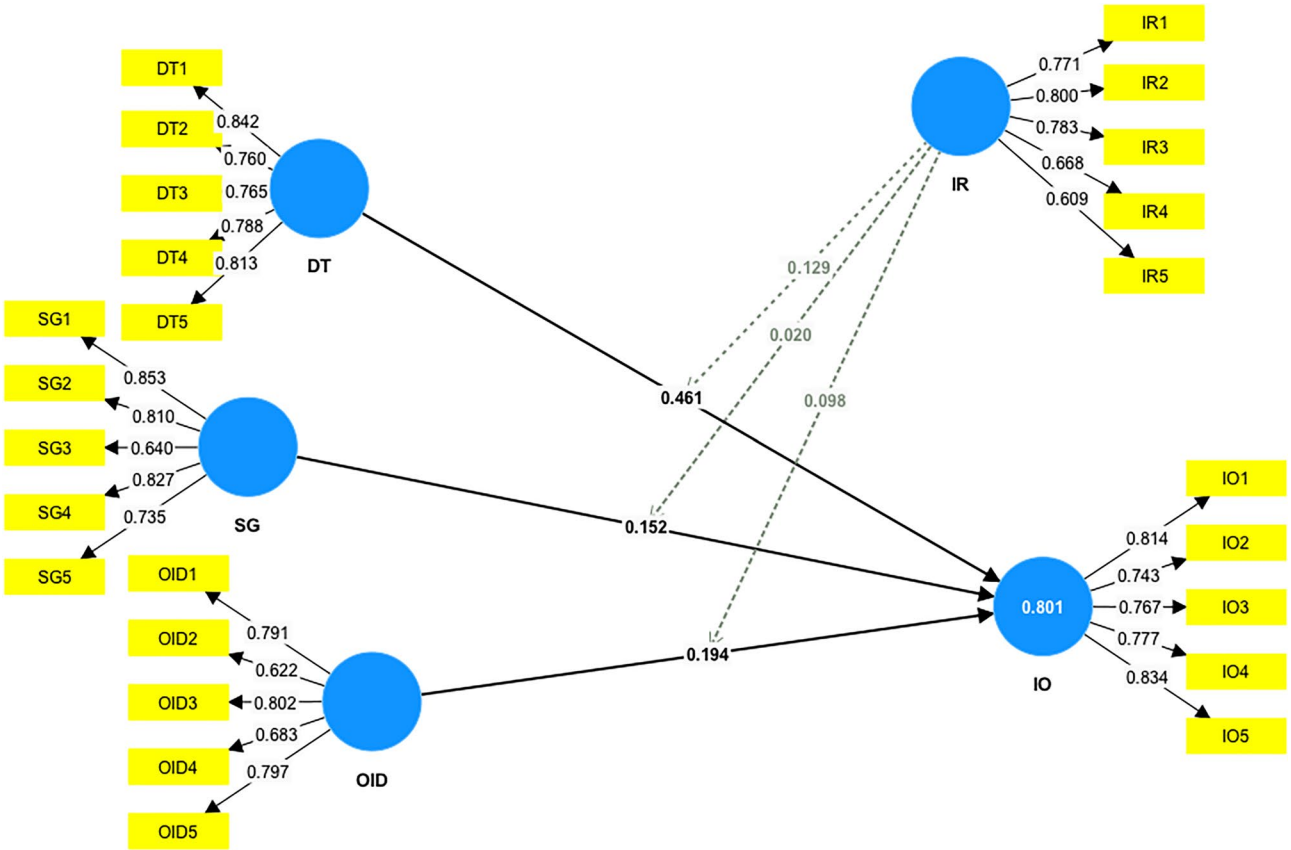

Fig. 1 SmartPls output file

Factor loadings for each item exceeded 0.60, and the AVE for each construct was above 0.50, showing that each latent factor accounted for at least half of the variance. These findings, summarized in Table 3, demonstrate strong, convergent validity.

The CFA results confirmed that all constructions showed good reliability, and convergent validity. All values surpassed the recommended thresholds, indicating no cross-loading issues. One item, from the excessive cognitive use construction had, a low factor loading and was, removed to maintain the overall reliability and validity of the constructs (see Fig. 1).

3.6 Discriminant validity

To ensure robustness, we checked discrimination, validity using several methods. First, we compared each construct's square root of AVE with inter-construct, correlations [69]. The results showed each construct's AVE was, higher than its inter-construct correlations, indicating no discriminant validity issues. Table 4 illustrates that each construct's AVE exceeds the respective variable correlations.

Table 4 Discriminant validity

Construct	DT	IO	IR	OID	SG	IR x DT	IR x SG	IR x OID
DT								
IO	0.897							
IR	0.868	0.786						
OID	0.659	0.689	0.719					
SG	0.450	0.490	0.822	0.771				
IR x DT	0.241	0.372	0.433	0.339	0.890			
IR x SG	0.286	0.254	0.339	0.227	0.134	0.867		
IR x OID	0.325	0.312	0.428	0.334	0.197	0.469	0.895	

Table 5 Factor loadings and reliabilities

Variables	Items	Factor Loading	Cronbach's alpha	Composite reliability	Average variance extracted
DT	DT1	0.842	0.855	0.895	0.631
	DT2	0.760			
	DT3	0.765			
	DT4	0.788			
	DT5	0.813			
IO	IO1	0.814	0.848	0.891	0.621
	IO2	0.743			
	IO3	0.767			
	IO4	0.777			
	IO5	0.834			
IR	IR1	0.771	0.785	0.85	0.533
	IR2	0.800			
	IR3	0.783			
	IR4	0.668			
	IR5	0.609			
OID	OID1	0.791	0.795	0.859	0.551
	OID2	0.622			
	OID3	0.802			
	OID4	0.683			
	OID5	0.797			
SG	SG1	0.853	0.836	0.883	0.603
	SG2	0.810			
	SG3	0.640			
	SG4	0.827			
	SG5	0.735			

Secondly, we examined cross-loading among constructs, and found them to be above the suggested level, indicating no cross-loading, problems. Table 5 shows that all values exceeded the recommended thresholds, confirming the robustness of the constructions. The absence of severe cross-loading issues further supports a high level of discriminant validity. These findings demonstrate that the constructions used in this study are both reliable and valid, providing a solid foundation for subsequent data analysis.

This table demonstrates the factor loadings, Cronbach's, alpha, composite reliability (CR), and average variance extracted (AVE) for each construct, indicating the reliability and, validity of the measurement scales used in the study.

3.7 Hypotheses testing

Before discussing the proposed hypothesized relationships, the results of the control variables are presented. Certain variables, such as firm size, industry type, and firm age, were controlled in the proposed research model under the assumption that these factors might influence, innovation output. The findings from the structural model validate this argument. However, except firm size, no significant effects of the control, variables were observed.

4 Discussion of results

H1 Digital transformation positively impacts innovation output

Consistent with prior research [41, 42], our results demonstrate a significant positive effect of, digital transformation on innovation output ($\beta = 0.371$, $p < 0.001$). The integration of advanced digital, technologies, such as artificial, intelligence (AI), the Internet of Things (IoT), and blockchain, plays a pivotal role in, facilitating the development of new products and services. This technological, integration significantly boosts, innovation output by enabling more efficient processes, fostering creativity, and opening new, avenues for innovation.

The positive impact of digital transformation on innovation, output underscores the importance of adopting cutting-edge technologies to stay competitive. Organizations,that,embrace digital transformation can, streamline operations, enhance decision-making, processes, and rapidly respond to market changes. This adaptability is, crucial for maintaining a competitive edge in today's fast-paced business environment.

Furthermore, the implementation of digital technologies such as AI, can automate routine tasks, allowing employees to, focus on more strategic and, creative activities. IoT can provide real-time data and insights, improving operational efficiency, and enabling the creation of smart products and services. Blockchain, technology can enhance, security and transparency, fostering trust and facilitating innovation in areas like supply chain, management and digital transactions.

These findings have several important implications for managers and decision-makers. First, investing in digital transformation, initiatives can significantly enhance an organization's innovation capacity. Managers should prioritize the integration of advanced digital technologies into their operations to drive innovation and improve overall performance. Additionally, fostering a culture that embraces digital transformation can help organizations adapt to technological changes and leverage new opportunities for innovation.

For researchers, these results highlight the critical role of digital transformation as a driver of organizational innovation. Future research could explore the specific mechanisms through which digital technologies influence innovation, processes and outcomes. Understanding these mechanisms can provide deeper insights into how organizations can effectively implement digital transformation strategies to maximize their innovation potential.

In conclusion, our findings support the notion that digital transformation is a critical driver of organizational innovation. By integrating advanced digital technologies, organizations can enhance their innovative output, stay competitive, and achieve sustainable growth. These insights provide valuable guidance for both practitioners and researchers seeking to understand and leverage the transformative power of digital technologies in driving innovation.

H2 Schumpeterian growth positively impacts innovation output

The findings confirm the positive influence of Schumpeterian growth on innovation output ($\beta = 0.395$, $p < 0.001$), aligning with previous studies[18, 19, 32, 52, 70–72]. Entrepreneurial activities and continuous innovation play pivotal roles in disrupting existing market structures and fostering economic development. Our results indicate that higher levels of entrepreneurial activity and innovation rates within industries significantly contribute to innovation output.

Schumpeterian growth theory emphasizes the importance of innovation-driven competition and the creation of new markets through entrepreneurial endeavors. This study supports the notion that entrepreneurial ventures and innovative efforts are crucial for economic growth and technological advancement. When businesses engage in continuous innovation, they not only enhance their own competitiveness but also stimulate the overall market dynamics by introducing new products, services, and business models.

The positive relationship between Schumpeterian growth and innovation output suggests that industries with robust entrepreneurial ecosystems are more likely to experience higher innovation rates. This finding highlights the importance of fostering an environment that supports entrepreneurship and innovation. Policymakers and industry leaders should consider implementing strategies and policies that encourage entrepreneurial activities, such as providing funding opportunities, reducing regulatory, barriers, and promoting collaboration between startups and established firms.

For managers, these findings underline the significance of investing in entrepreneurial initiatives and innovation processes. By fostering a culture of innovation, within their organizations, managers can drive continuous improvement, and stay ahead of market trends. Encouraging risk-taking, creativity, and experimentation can lead to breakthrough innovations that disrupt traditional market structures and create new opportunities for growth.

From a research perspective, these results contribute to the, understanding of how Schumpeterian growth mechanisms operate within contemporary industries. Future, studies could delve deeper into the specific factors that enhance, entrepreneurial activity and innovation rates, such as the role of technology, access to capital, and the impact of educational and training, programs. Additionally, exploring the interaction between Schumpeterian growth, and other economic and organizational factors can provide a more comprehensive understanding of innovation dynamics.

In conclusion, the positive influence of Schumpeterian growth on innovation output underscores the critical role of entrepreneurship and continuous, innovation in driving economic development and market transformation. These insights offer valuable implications for, policymakers, industry leaders, and researchers aiming to enhance innovation ecosystems, and promote sustainable economic growth.

H3 Open innovation dynamics positively impact innovation output

The results reveal a significant positive effect of open, innovation dynamics on innovation output ($\beta = 0.409$, $p < 0.001$). This finding is consistent, with prior research [33–35, 56], which highlights the, benefits of external collaborations in enhancing a firm's innovative capabilities. By leveraging external knowledge and resources, firms can significantly boost their innovative output.

Open innovation involves the strategic use of external ideas and pathways to advance internal innovation. This approach allows firms to tap into a broader pool of knowledge and expertise, accelerating the innovation process. External collaborations, such as partnerships with other companies, academic institutions, and research organizations, provide access to new technologies, insights, and markets that might otherwise, inaccessible.

The positive impact of open innovation dynamics on innovation, output underscores the importance of building strong networks and collaborative relationships. Firms that actively seek and incorporate external input are better positioned to develop novel products and services, improve processes, and respond to market changes more effectively. Our findings extend the work of Chesbrough [44] by showing that external collaborations significantly amplify innovation outcomes when supported by internal cross-functional teamwork. This approach not only enhances their innovative capacity but also reduces the risks and costs associated with innovation by sharing them with partners.

For managers, these findings highlight the value of fostering an open innovative culture within their organizations. Encouraging collaboration and knowledge-sharing with external entities can lead to more creative solutions and faster, development, cycles. Managers should consider strategies to build and maintain robust external networks, such as engaging in joint, ventures, participating in innovation clusters, and leveraging crowdsourcing, platforms.

From a policy perspective, supporting mechanisms that facilitate open innovation can be beneficial for the broader economy. Policymakers can promote open innovation by providing incentives for collaboration, creating innovation hubs, and ensuring intellectual property laws that protect collaborative ventures while encouraging knowledge exchange.

Future research could explore the specific types of external collaborations that are most effective in different contexts and industries. Additionally, investigating the challenges and barriers to open innovation can provide deeper insights into how firms can overcome these obstacles and maximize the benefits of external collaborations.

In conclusion, the significant positive effect of open innovation dynamics on innovation output emphasizes the critical role, of external collaborations in driving, innovation. Firms that embrace open innovation can enhance their innovative capabilities and achieve greater success in the competitive marketplace. These insights offer valuable implications for managers, policymakers, and researchers aiming to foster a more collaborative, and innovative business environment.

H4 Inter-rationality moderates the relationship between digital, transformation and innovation output, such that the relationship is stronger when inter-rationality is high

The findings indicate that inter-rationality significantly enhances, this relationship ($\beta = 0.298$, $p < 0.01$). This supports the hypothesis that digital transformation is more effective in driving innovation output when there is high interdisciplinary and, cross-functional collaboration.

High levels of inter-rationality, characterized by effective, knowledge integration and teamwork, amplify the benefits of digital technologies. When different departments and functions within an organization work together seamlessly, they can better leverage digital tools and insights, leading to greater innovation. This collaboration fosters an environment where ideas can be freely exchanged, and diverse perspectives can contribute to more innovative solutions.

For managers, these findings underscore the importance of fostering inter-rationality within their organizations. Promoting interdisciplinary and cross-functional collaboration can enhance the impact of digital transformation efforts. Managers should encourage open communication, create opportunities for team collaboration, and implement, structures that facilitate knowledge sharing across different functions.

From a practical standpoint, organizations should invest in training programs that build collaborative skills and create platforms for cross-functional teams to work together on innovative projects. By doing so, they can ensure that digital transformation initiatives are supported by a strong collaborative culture, maximizing their potential, to drive innovation.

Future research could explore the specific mechanisms through which inter-rationality enhances the effectiveness of digital transformation. Additionally, investigating how different types of inter-rationality (e.g., formal versus informal collaboration) impact, innovative outcomes could provide deeper insights. Understanding these dynamics can help organizations tailor their strategies to foster the most effective forms of collaboration.

In conclusion, the moderating role of inter-rationality highlights the critical importance of collaboration in maximizing the benefits of digital transformation. Organizations that promote high levels of interdisciplinary and cross functional, teamwork are better positioned to leverage digital technologies for greater innovation, output. These insights offer valuable guidance for managers and policymakers aiming to enhance innovation, through effective collaboration and digital transformation initiatives.

H5 Inter-rationality moderates the, relationship between Schumpeterian growth and innovation output, such that the relationship is stronger when inter-rationality is high

The results reveal a significant moderating effect of inter-rationality on the, relationship between Schumpeterian growth and innovation, output ($\beta = 0.312$, $p < 0.01$). This finding supports the notion that entrepreneurial activities and continuous innovation are more impactful when bolstered by strong interdisciplinary collaboration. Inter-rationality enhances the translation of entrepreneurial efforts into tangible innovation and outcomes.

Inter-rationality, which involves effective collaboration and knowledge sharing across different disciplines and functions, amplifies the benefits, of entrepreneurial activities. When teams from various backgrounds and expertise areas work together, they can better, harness entrepreneurial initiatives, leading to more significant and practical, innovation outputs. This synergy allows for a more holistic approach to problem-solving and innovation, integrating diverse perspectives and skills.

For managers, these findings highlight the importance of fostering a, collaborative culture that promotes interdisciplinary teamwork. Encouraging departments to work together and share knowledge can enhance the impact of entrepreneurial, activities on innovation output. Managers should implement strategies that facilitate collaboration, such as, cross-functional teams, joint projects, and regular inter-departmental meetings.

Practically, organizations should focus on creating environments that support inter-rationality. This can include investing in collaborative tool, and technologies, developing spaces that encourage teamwork, and offering training programs, that enhance collaborative skills. By fostering strong interdisciplinary collaboration, organizations, can better translate entrepreneurial activities into successful innovation outcomes.

Future research could delve deeper into the specific aspects of,inter-rationality that most effectively enhance the relationship between entrepreneurial activities, and innovation output. Additionally, exploring how different organizational structures and cultures impact this relationship can provide valuable insights for tailoring strategies to various, contexts.

In conclusion, the significant moderating effect of inter-rationality on, the relationship between Schumpeterian growth and innovation output underscores, the critical role of interdisciplinary collaboration. Organizations that cultivate a collaborative environment are better equipped to convert entrepreneurial activities into tangible innovations, driving greater success and competitiveness. These findings offer practical, guidance for managers and valuable directions for future research in innovation management.

H6 Inter-rationality moderates the relationship between open innovation, dynamics and innovation output, such that the relationship is, stronger when inter-rationality is, high

Inter-rationality moderates the relationship between open, innovation dynamics and innovation output, making the relationship stronger when,inter-rationality is high. The findings confirm that inter-rationality significantly enhances this relationship ($\beta = 0.324$, $p < 0.01$). This supports the hypothesis that the positive impact of open innovation on innovation output is amplified when inter-rationality is high. Effective collaboration, and the integration of external knowledge are crucial for maximizing the benefits of open, innovation initiatives.

Inter-rationality, which involves seamless collaboration, and knowledge sharing across different disciplines and functions, enhances the effectiveness of open, innovative dynamics. When organizations effectively integrate external, knowledge and resources, they can better leverage open innovation to drive significant innovation outcomes. This integration ensures that external ideas are not just adopted but are also synergized with internal, capabilities, leading to more robust and impactful innovations.

For managers, these findings emphasize the importance of fostering a collaborative culture that promotes inter-rationality. Encouraging teamwork, and knowledge sharing, across different departments and with external partners can significantly enhance the benefits of open innovation initiatives. Managers should create environments that facilitate effective collaboration, such as cross-functional teams, joint innovation, projects, and platforms for external collaboration.

Practically, organizations should invest in tools and systems that support inter-rationality. This includes collaborative software, spaces designed for teamwork, and training programs that enhance collaborative skills. By fostering an environment, where inter-rationality thrives, organizations can better harness the potential of open innovation and achieve higher innovation output.

Future research could explore the specific mechanisms through which inter-rationality enhances the relationship between open innovation dynamics, and innovation output. Additionally, investigating how different types of external collaborations (e.g., partnerships with startups, academic institutions, or other firms) interact, with inter-rationality can provide deeper insights.

In conclusion, the significant moderating effect of inter-rationality on the relationship between open innovation dynamics and innovation, output highlights the critical role of effective collaboration and knowledge integration. Organizations that foster strong inter-rationality can better maximize the benefits of open innovation, leading to, greater innovation success. These findings provide valuable guidance for managers and offer promising directions for future research in innovation management.

In summary, the results from the structural analysis (see Table 6) support all, six hypotheses. Digital, transformation (H1: $\beta = 0.371$, $p < 0.001$), Schumpeterian growth (H2: $\beta = 0.395$, $p < 0.001$), and open innovation dynamics (H3: $\beta = 0.409$, $p < 0.001$) positively, impact innovation output. Additionally, inter-rationality significantly, moderates the relationships between digital transformation (H4: $\beta = 0.298$, $p < 0.01$), Schumpeterian, growth (H5: $\beta = 0.312$, $p < 0.01$), and open innovation dynamics (H6: $\beta = 0.324$, $p < 0.01$) and innovation, output. Therefore, the structural analysis confirms, that these variables are significant predictors, of innovation output.

The table above presents the hypothesis testing, results, demonstrating that all six hypotheses are supported. The path coefficients indicate the strength of the relationships, while the t-values and standard errors provide, statistical significance and reliability of the estimates. The, findings confirm that digital transformation, Schumpeterian growth, and open, innovation dynamics positively influence innovation, output, with inter-rationality enhancing these effects.

Table 6 Hypothesis testing results

Hypothesis	Path	Beta	Standard deviation	T value	*p* values	Result
H1	DT —> IO	0.461	0.051	9.038	0.000	Accepted
H2	OID —> IO	0.194	0.072	2.692	0.007	Accepted
H3	SG —> IO	0.152	0.050	3.008	0.003	Accepted
H4	IR x DT —> IO	0.129	0.052	2.501	0.012	Accepted
H5	IR x SG —> IO	0.120	0.033	3.637	0.000	Accepted
H6	IR x OID —> IO	0.098	0.025	3.920	0.000	Accepted

5 Discussion summary

The findings of this study provide critical insights into the interplay between digital transformation (DT), Schumpeterian growth (SG), open innovation dynamics (OID), and innovation output (IO), positioning inter-rationality as a key moderating variable. While prior research has examined these constructs independently, this study offers an integrated perspective, demonstrating their interconnected influence on innovation performance. The results not only reinforce established theoretical expectations but also challenge the prevailing assumption that digital transformation and Schumpeterian growth are sufficient drivers of innovation output. Instead, the findings underscore the indispensable role of inter-rationality in amplifying these effects, suggesting that innovation is not solely a function of technological capability or entrepreneurial dynamism but rather a product of strategic cross-functional collaboration.

The positive and significant impact of digital transformation on innovation output ($\beta = 0.312$, $p < 0.01$) aligns consistent with Bharadwaj et al. [38] and Vial [39] that digital technologies enhance operational efficiency, agility, and innovation capabilities which highlights the transformative potential of digital technologies in optimizing operational efficiency and enhancing knowledge absorption. However, this study moves beyond conventional discourse by demonstrating that technological adoption alone does not maximize innovation outcomes—rather, the extent to which firms integrate digital tools within an interdisciplinary, collaborative structure determines their effectiveness. Similarly, the moderate yet significant effect of Schumpeterian growth ($\beta = 0.279$, $p < 0.05$) reaffirms the role of entrepreneurial disruption in fostering industry evolution. Nonetheless, this effect appears contingent on firms' ability to balance creative destruction with knowledge diffusion, a dimension often overlooked in conventional Schumpeterian analyses.

Notably, open innovation dynamics exhibited the strongest impact on innovation output ($\beta = 0.409$, $p < 0.001$), reinforcing the argument that external knowledge flows and inter-organizational collaborations are central to sustained innovation. This finding challenges traditional firm-centric innovation models that prioritize internal R&D over boundary-spanning knowledge exchange. Moreover, the study identifies inter-rationality as a critical enabler, with its strongest moderating effect observed in the relationship between OID and innovation output ($\beta = 0.324$, $p < 0.001$). This suggests that firms deriving the greatest benefits from open innovation are those that institutionalize interdisciplinary cooperation, allowing them to fully exploit external knowledge networks. Similarly, inter-rationality significantly strengthened the effects of digital transformation ($\beta = 0.298$, $p < 0.01$) and Schumpeterian growth ($\beta = 0.312$, $p < 0.01$), reinforcing the idea that technological advancements and entrepreneurial initiatives yield superior outcomes when embedded in collaborative structures.

The theoretical and practical implications of these findings are profound. Theoretically, this study bridges gaps in dynamic capabilities theory and innovation ecosystem theory by illustrating how digital transformation, entrepreneurial growth, and open innovation interact within a moderated framework. It also extends the discourse on inter-rationality, positioning it as a strategic capability rather than a mere operational variable. Practically, the findings urge firms to move beyond siloed innovation strategies and adopt a more systematic, integrative approach that fosters cross-functional collaboration. In the absence of strong inter-rationality, investments in digital transformation and open innovation may yield suboptimal results, ultimately constraining firms' ability to sustain long-term innovation performance.

Overall, this study underscores the imperative of rethinking innovation management through a holistic, collaborative lens. While digital transformation, Schumpeterian growth, and open innovation are individually important, their full potential is only realized when firms embed these processes within an interdisciplinary, knowledge-sharing ecosystem. This research thus calls for a paradigm shift in how firms approach innovation—one that moves away from isolated technological or entrepreneurial efforts and toward integrated, relationally driven innovation frameworks.

6 Conclusion

Innovation plays a central role in economic growth by enhancing organizational competitiveness and contributing to national productivity. This study explored how digital transformation, Schumpeterian growth, and open innovation dynamics shape innovation output, especially when moderated by inter-rationality. Based on responses from 300 professionals—including innovation managers, R&D directors, and senior executives—the results confirm that all three independent variables significantly predict innovation performance.

Digital transformation (H1) showed a strong positive effect on innovation output ($\beta = 0.371$, $p < 0.001$), indicating that firms embracing advanced digital tools tend to be more innovative. Schumpeterian growth (H2) also positively influenced innovation output ($\beta = 0.395$, $p < 0.001$), supporting the idea that entrepreneurial activity and creative destruction drive innovation. Similarly, open innovation dynamics (H3) had a strong effect ($\beta = 0.409$, $p < 0.001$), highlighting the role of external collaboration in enhancing innovation capabilities. Inter-rationality significantly moderated these relationships, suggesting that cross-functional and interdisciplinary collaboration amplifies the impact of all three predictors.

Grounded in Dynamic Capabilities Theory and Innovation Ecosystem Theory, the findings suggest that digital transformation equips firms with tools, Schumpeterian growth provides the entrepreneurial drive, and open innovation dynamics enable effective knowledge sharing. Together, they form a robust framework for enhancing innovation output.

Finally, the impact of digital transformation is not uniform across sectors. Industries with high digital maturity and strong infrastructure gain more from digital adoption than traditional sectors, which often face cultural and technical barriers. Similarly, weak digital infrastructure—such as poor internet access or limited policy support—can constrain innovation, especially in emerging economies. These contextual differences highlight the need for tailored digital strategies to unlock innovation potential.

7 Implications

7.1 Managerial implications

This study offers practical insights for organizations, contemplating the adoption of digital technologies and open innovation, practices. It highlights how digital transformation, entrepreneurial activities, and open innovation can boost innovation output. Furthermore, the findings guide managers on the significance of promoting interdisciplinary collaboration to fully leverage these initiatives. The research also delivers crucial insights for researchers and policymakers, emphasizing the potential of integrated innovation, strategies to drive organizational growth and enhance competitiveness.

Managers must integrate Digital Transformation (DT), Schumpeterian Growth (SG), and Open Innovation Dynamics (OID) strategically to achieve the highest innovation yield. This entails treating DT as more than just a software uplift; rather, it becomes an innovative enabler mandating investment in digital skills, agile work environments, and cross-functional collaboration. Second, SG entrepreneurial endeavors need to be supported. Firms must embrace creative and destructive approaches with continuous experimentation on new business models and organizational culture for innovation. The third point is an OID that will facilitate the absorption of external knowledge; managers must develop solid partnerships with universities, research institutions, and external innovators while assuring that internal teams are equipped to integrate external knowledge effectively. The highlighted insights indicate that firms need to develop digital adoption alongside dynamic capabilities and collaborative capabilities for sustaining innovation-driven competitive advantage.

7.1.1 Theoretical implications

This study advances theoretical development by expanding existing literature on the impact of digital, transformation, Schumpeterian growth, and open innovation dynamics on innovation output. It introduces a, comprehensive model that examines the moderating role of inter-rationality in these relationships. These empirical findings offer a foundation for refining and expanding theoretical frameworks, enhancing our, understanding of the factors driving innovation in today's technological and economic landscapes.

Furthermore, macro-level conditions create enabling or restrictive environments for DT-driven innovation, meaning that policy interventions, industry-specific digital strategies, and cross-sector collaborations are essential for maximizing the benefits of DT. Future research should explore how regulatory environments, R&D investments, and institutional support further shape the relationship between DT and innovation performance across different economic settings.

7.1.2 Contribution of study

The study contributes to Digital Transformation Theory by demonstrating that DT's impact on innovation output is contingent on how firms integrate entrepreneurial capabilities (SG) and external knowledge flows (OID), rather than being a

direct outcome of technology adoption. It advances Schumpeterian Growth Theory by showing that digital transformation accelerates creative destruction, reshaping industries through continuous digital innovation. Additionally, it extends Open Innovation Theory by highlighting that OID's effectiveness in enhancing innovation depends on digital readiness and cross-functional collaboration, reinforcing the role of inter-rationality in digital ecosystems.

8 Limitations and future directions

8.1 Limitations

This study, while providing valuable insights, has several limitations that need to be addressed. Firstly, the data was collected at a single point in time, which limits our ability to observe changes and trends over time. This cross-sectional design restricts our understanding of the long-term effects and causal relationships between digital transformation, Schumpeterian growth, open innovation dynamics, and innovation output.

Secondly, the study focused solely on organizational factors influencing innovation output, without considering external environmental factors such as, market conditions, regulatory changes, and technological advancements. This narrow focus may not provide a comprehensive understanding of the dynamics influencing innovation.

Furthermore, the sample used in this study may not, be representative of all industries and sectors, which limits the generalizability of, the findings. Different industries may exhibit unique innovation patterns and challenges, and our results may, not fully capture these differences.

8.2 Future directions

To address these limitations, future research should consider several directions. Firstly, longitudinal studies are needed to observe changes and trends over time. This approach will provide deeper insights into the long-term effects, and causal relationships that are not evident in cross-sectional research. Longitudinal data can help, capture the evolution of digital transformation, Schumpeterian growth, and open innovation, dynamics and their impact on innovation output.

Secondly, future studies should investigate the influence of external environmental factors on innovation. Exploring market conditions, regulatory, changes, and technological advancements will offer a more holistic view of the dynamics of play. Understanding these external influences can reveal how external pressures and opportunities shape organizational innovation strategies.

Additionally, expanding the scope of research to include various industries and sectors will enhance the generalizability of the findings. By examining different industries, future, research can uncover unique innovation patterns and challenges, providing a, broader perspective.

Cross-cultural studies should also be conducted to explore how cultural differences impact the relationships between the key constructs studied. This will help determine if the findings are universally applicable or context-specific, offering insights into how different, cultural contexts influence innovation dynamics.

Identifying and examining other potential moderating variables, such as organizational culture, leadership styles, and resource, availability, can provide a more nuanced understanding of the factors that enhance or hinder innovation. This can help develop more targeted strategies for fostering innovation within, organizations.

Incorporating qualitative research methods, such as case studies and interviews, will also be valuable for gaining in-depth insights into the processes, and practices underlying digital transformation and innovation. Qualitative data can complement quantitative findings and offer rich, contextualized understanding.

Finally, future research should explore the role of emerging technologies, such as artificial intelligence, blockchain, and the Internet of Things, in shaping innovation, dynamics. Investigating how these technologies interact with existing digital transformation efforts and contribute to innovation output will provide valuable insights into the future of innovation, management.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request. This ensures that the data can be accessed for verification and further research purposes as needed.

Declarations

Ethics approval and consent to participate The research was conducted in compliance with the ethical guidelines of the Institutional Review Board (IRB) at the University of Lahore. The protocol was approved by the IRB at the University of Lahore, in accordance with relevant ethical guidelines and regulations. All procedures followed the ethical standards for research involving human subjects as set forth by the committee.

Consent to publication Not applicable.

Informed consent Informed consent was obtained from all participants involved in the study. Each participant was provided with comprehensive information about the purpose, nature, and potential impacts of the research. Participants gave their voluntary consent to participate, understanding that they could withdraw from the study at any time without any repercussions. For participants under the age of 16, consent was obtained from their parent or legal guardian.

Clinical trial Not applicable.

Competing interests The authors declare no competing interests.

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