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RESEARCH ARTICLE

Digital Construction Led Growth Asymmetries in Europe: The Need for Collaborative Culture

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Abstract

This study delves into the exploration of asymmetries in the field of Digital Economics (DE) and specifically, within the digital construction sector, unravelling intricate relationships that guide its evolutionary journey. To unveil the complex relationship between GDP growth rates and Digital Construction (DC) we leverage the Digital Economy and Society Index (DESI), employing a panel dataset encompassing 27 European Union (EU) countries over the period 2017-2022. As a foundational tool for our empirical analysis, we perform Quantile via Moments regression, thus introducing this novel methodology to digital construction research. The findings reveal a consistent and statistically significant positive impact of DC on GDP growth rates, across the entire spectrum of economic conditions, but the effect is more pronounced at the upper quantiles of output. This result implies that stronger economies can use more efficiently the benefits of the Digital Construction compared to the weaker economies, thus signalling the need of the latter for structural reforms, to improve the integration rate of digitalization in the construction sector. The

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pronounced influence of the Human Capital component of DC underscores the pivotal role of nurturing human skills to effectively integrate digital construction techniques into infrastructure development, within a collaborative culture. By fostering a culture of innovation, collaboration and enabling the integration of digital construction techniques, the weaker economies can position themselves for higher growth rates and competitiveness in an ever-changing world.

Keywords

Digital Construction; Digital Economics; GDP Growth; Collaborative Culture; Asymmetries; Infrastructure; Circular Economy

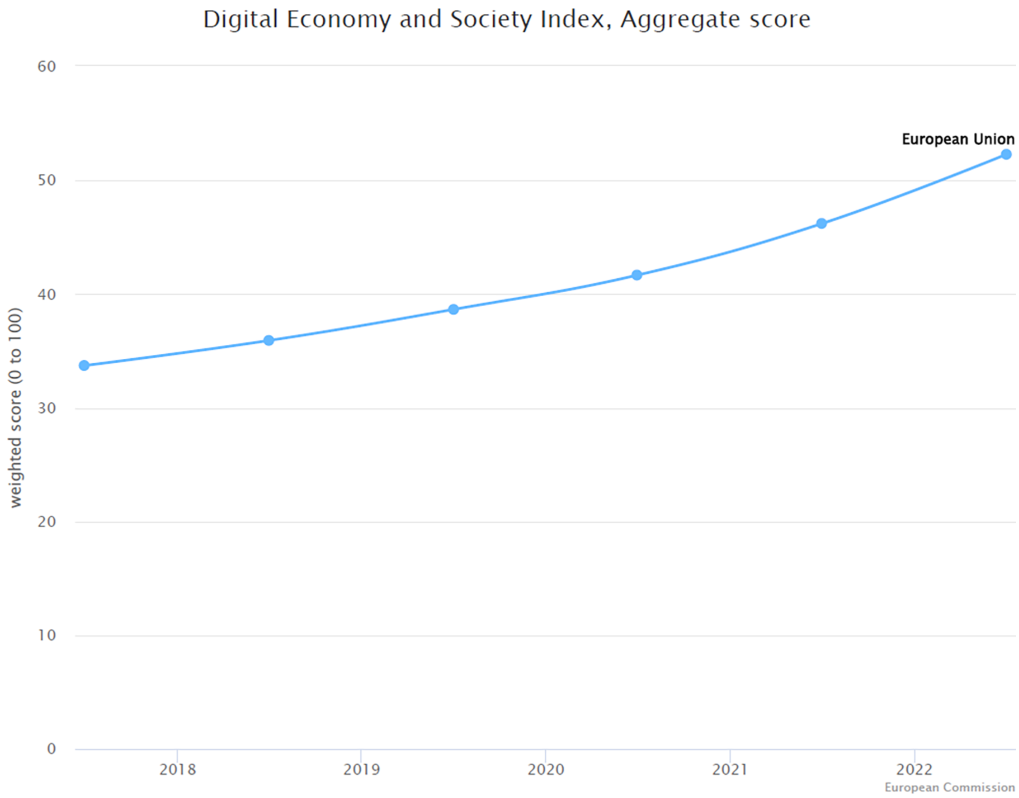
JEL Classification

C31; L74; M14; O18; O31

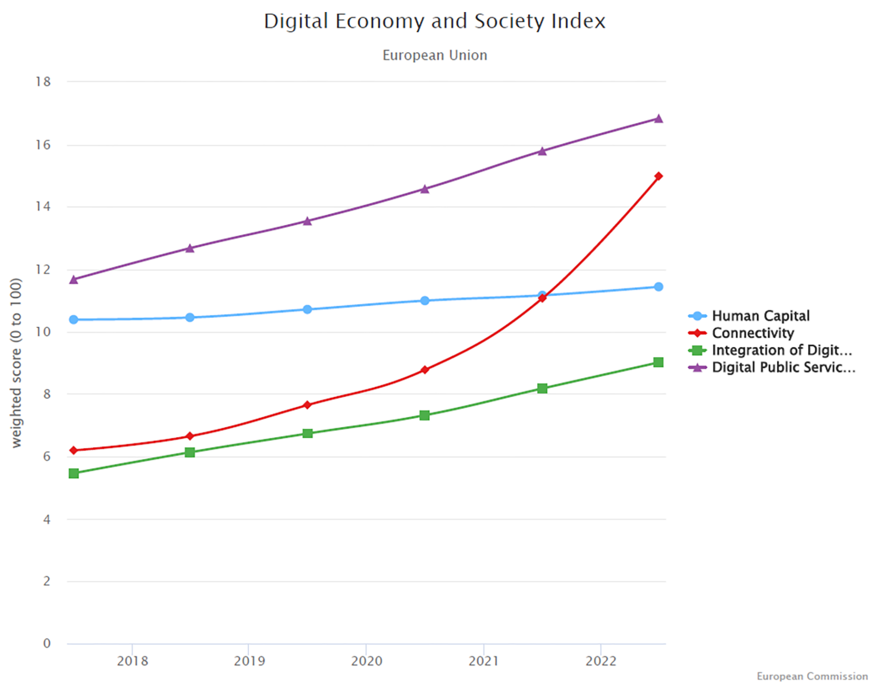
Introduction

One of the main challenges that the construction sector faces is the adoption and integration of digital technologies. Setaki and van Timmeren (2022) mention that the building industry is the most wasteful industry worldwide (especially the construction and demolition phases) and very conservative in adopting new technologies, mainly in the initial construction stages. In addition, as Sawhney et al. (2014) mention, even the Information and Communication Technology (ICT) sector for construction faces numerous challenges as it is characterized by fragmentation. In 2021, construction activities rebounded back to pre-pandemic levels in most major economies and as a result buildings energy demand increased by around 4 per cent from 2020 which is the largest increase in the last 10 years (UNEP, 2022). Further, according to the same source, buildings and construction sector is not on track to achieve decarbonization by 2050. The above findings are also in line with a survey conducted by Deloitte (2019), according to which even though Digital Construction (DC), namely the utilization of digital technologies to construct more efficiently and with higher level of quality, can be the answer to major challenges like climate change, sustainability, lagging productivity and financial pressure, the construction industry has underinvested in technology. It's worth mentioning that only 1.2% of the sector's revenue is allocated for Information Technology (IT), as opposed to 3.5% on average for the rest industrial sectors (Deloitte, 2019).

Despite the slow pace of the progress observed in the adoption and integration of digital technologies in the construction sector, a growing number of researchers has focused on examining the importance of digitalization in the construction sector, as a key element to promote the Circular Economy (CE). The bibliometric analysis of the literature review conducted by Rodrigo, et al. (2023) revealed that the vast majority of publications (91%) took place after 2018, while the increase in the number of publications reached 370% during the period 2019-2022. This evidence shows a growing research interest, from academic, public and private institutions, for the impact of Digital Construction on the economy in general and specifically on the circular economy. Among them, KPMG's (2021) comprehensive analysis on the "Value of Data in Construction" provides a detailed examination of how data-driven approaches are shaping the sector. Equally noteworthy is the exploration of "Information Management," a report that delves into the effective handling and utilization of information within the construction context (KPMG, 2021). The Royal Institute of Chartered Surveyors (RICS, 2022) contributes significantly with their report on "Digital Twins," shedding light on the innovative concept of creating virtual replicas of physical structures and their implications for the industry. Additionally, the European Union's report on "Budgeting in the Digital Construction" offers a valuable perspective on financial planning and management within the digital construction realm (BIM Summit, 2021). Moreover, European Commission collects valuable data concerning the DESI index (Digital Economy and Society Index), which is a composite index that summarizes relevant indicators on Europe's



Graph 1. European Union-DESI overall index, calculated as the weighted average of the four main DESI dimensions.



Graph 2. European Union-DESI dimensions (Human Capital-hc, Connectivity-con, Integration of Digital Technology-idt, Digital Public Services-dps)

digital performance and tracks the evolution of EU Member States, across different digital dimensions: Connectivity, Human Capital, Integration of Digital Technology and Digital Public Services (Graphs 1-2).

Collectively, these indispensable reports cast a spotlight on the multifaceted impact of building information modelling (BIM) led digital transformation on both societal and technological dimensions (Sawhney, et al., 2014). However, a notable void exists in the landscape of research – the scarcity of a comprehensive report that meticulously dissects the intricate economic effects of the broader digital construction landscape on a nation's Gross Domestic Product (GDP).

Aim, Objectives, and Contribution

Therefore, the focal research inquiry of this paper revolves around an in-depth exploration of the multifaceted elements that encompass the domain of digital construction. Additionally, the study aims to delve into the intricacies of lead growth asymmetries within this context. Furthermore, the overarching objective of this research endeavour is twofold: firstly, to establish a robust foundation underscoring the significance of digital construction; and secondly, to expound upon the consequential policy implications stemming from its integration.

In essence, this paper embarks on a comprehensive journey to encompass led growth asymmetries – an area of paramount importance within the digital construction landscape. By scrutinizing these imbalances, the study strives to uncover critical insights into the factors influencing disparities in progress and development. Further, our paper extends its reach to various contributing factors that shape the realm of digital construction. It seeks to shed light on the intricate dynamics that underlie the field, encompassing technological advancements, collaborative frameworks, and transformative processes. Beyond this analytical exploration, the research is committed to casting digital construction in its rightful significance. It seeks to construct a compelling narrative that underscores the pivotal role of digital construction in reshaping traditional paradigms, enhancing efficiency, and fostering innovation within the construction sector. Through a meticulous review of existing literature and empirical evidence, we endeavour to establish a compelling rationale for the integration of digital construction practices. Lastly, the paper pivots towards the practical realm by examining the policy implications inherent in the digital construction arena. By extrapolating from the insights gained, the study aims to offer strategic recommendations and guidelines that could potentially guide policymakers, industry stakeholders, and decision-makers towards a more informed and effective approach to digital construction implementation. Thus, the research not only aims to enrich academic discourse but also to serve as a compass for informed decision-making in the realm of construction's digital transformation.

The paper's research question is poised to unveil the intricacies of digital construction, and it aspires to contribute substantively by delving into lead growth asymmetries and offering a comprehensive perspective on the significance and policy ramifications of digital construction within the broader construction landscape.

Our contribution to the literature is as follows: Firstly, this research introduces a pioneering approach by utilizing Quantile via Moments regressions (Machado and Santos Silva, 2019) within a panel setting in the realm of digital construction. To the best of current knowledge, this innovative methodology has not been previously applied within the context of digital construction research. This novel analytical framework enables a deeper exploration of the complex interactions among variables, transcending conventional methodologies and offering fresh insights. Secondly, a distinctive focal point of this investigation is the exploration of asymmetries within the digital construction sector. This study uniquely addresses this aspect, shedding light on the intricate relationships that govern the sector's evolution. By empirically substantiating the presence of non-Gaussian effects resulting from the impact of digital construction on GDP growth rates, which is more pronounced in the richer countries, this research challenges established assumptions and contributes to a more nuanced understanding of the economic implications of digital construction.

Third, this study makes a significant contribution to an underrepresented area of research by substantially expanding the limited literature concerning the nexus between digitalization and economic performance (context of digital construction). Through meticulous analysis of empirical data, we provide valuable insights and empirical evidence that enrich our comprehension of how digitalization shapes and influences economic outcomes. By delving into this complex relationship, this study enhances the broader understanding of the mechanisms that drive economic growth within the context of digital construction.

The subsequent structure of this paper is delineated as follows: In Section 3, a succinct yet comprehensive review of pertinent literature is presented, with a focal emphasis on the impact of digitalization on economic growth and the effects of collaborative culture in taking full advantage of the benefits of digitalization in the construction sector, thereby situating the research within the broader academic dialogue. Section 4 subsequently elucidates the intricacies of the data employed and explicates the econometric methodology employed, laying the foundational groundwork for the ensuing presentation of empirical findings. Section 5 serves as the locus for the unveiling and contemplative analysis of results, engendering insightful discussions that elucidate the implications of the findings. Section 6 encapsulates the study's essence by offering a succinct synthesis of its pivotal findings and contributions, culminating in a conclusive wrap-up that encapsulates the broader ramifications of the study and potentially illuminates avenues for future exploration. Further, in this very section, we provide policy implications and strategic guidelines for practitioners, by imparting judicious policy recommendations derived from empirical insights, effectively bridging the research with real-world applications. Lastly, section 7 summarizes the results and concludes.

Literature Review

As revealed by several studies (Table 1), digital technologies in construction are leading to significant changes in productivity, cost efficiency, safety, resource management, energy efficiency, and error reduction. McKinsey and Company (2023) found that the use of advanced analytics in an oil and gas company improved productivity in engineering functions by 20-25%. Deloitte Insights (2023) highlighted a case where digital modelling and prefabrication reduced construction time by over six months compared to traditional methods. TechGig (2023) noted the implementation of AI and machine learning for safety monitoring, along with clash detection tools and on-site sensors, can reduce workplace accidents and save

Table 1. Major Digital Construction Reports

Impact Area	Description	Source
Increase in Productivity	Advanced analytics improved productivity by 20-25% in engineering functions.	McKinsey and Company, 2023
Cost Reduction and Efficiency	Digital modelling and prefabrication reduced construction time by over six months.	Deloitte Insights, 2023
Improved Safety and Reduced Accidents	AI, machine learning, and sensor technologies reduce accidents and related costs.	TechGig, 2023
Resource Management and Inventory Control	IoT and NFC technologies, including RFID tracking, enhance inventory management and reduce costs.	McKinsey and Company, 2023
Energy Efficiency	Building analytics improve energy efficiency, leading to long-term cost savings.	TechGig, 2023
Reduction in Rework and Errors	A mobile app for defect tagging in BIM models led to a 12% decrease in rework hours.	McKinsey and Company, 2023

costs. Additionally, McKinsey and Company (2023) emphasized the role of IoT and NFC technologies in improving inventory management and reducing costs through RFID tracking. Building analytics, part of digital construction, are also key in enhancing energy efficiency, leading to long-term cost savings for building operators and owners (TechGig, 2023). Finally, the introduction of a mobile app for defect tagging against BIM models led to a 12% reduction in rework hours at a construction site (McKinsey and Company, 2023).

Reports from RICS (2023) and Hitachi (2023), along with Krysten's (2020) earlier analysis, have broadly emphasized the added value of digital construction in the Architecture, Engineering, Construction, and Operations (AECO) sector. This perspective offers a more encompassing view of the transformative impact digital technology has on the industry. These insights are drawn from an extensive examination of the evolving landscape in construction, as thoroughly documented in the detailed reports and studies by TechGig (2023), McKinsey and Company (2023), and Deloitte Insights (2023). These sources collectively provide a nuanced understanding of how digital advancements are reshaping the AECO sector.

Concerning the impact of various factors of digital economy on the economic growth, Zhang, et. al. (2022) examine the impact of digital economy on the economic growth of a panel of countries along the "Belt and Road" before the COVID-19 pandemic (2009-2019) as well as the impact of the pandemic on the digital industry and trade pattern. They find empirical evidence of regional imbalances concerning the stage of digital economy's development along the examined countries with West Asia (except for Israel), Central Asia, and South Asia lagging. Further, they find that digital economy has a statistically significant effect on the economic growth, mainly through the channel of promoting industrial structure upgrading, the total employment and restructuring of employment, and that the pandemic increased the demand for digital industries more that the corresponding supply. Mura and Donath (2023) examine the impact of digitalization on economic growth in the European Union, using a sample of balanced panel data including 28 cross-sections during the period 2000-2021. To account for the impact of digitalization of economic growth they use the DESI (Digital Economy and Society Index) index. In line with the results of Zhang, et al. (2022), they find a statistically significant and positive impact if digitalization on economic growth. Wu and Yu (2022) examine the contribution of digital economy on economic growth of China as well as on the total factor productivity. Their results show that digital economy has been the most significant contributor in the country's economic growth over the past two decades. Concerning the economy of China, Zhang, et al. (2021) also find evidence that digital infrastructure, digital industry and digital fusion positively affect the regional total factor productivity.

In the study by Yousefi (2011), the focus centres on examining the influence of digitalization on the economic growth trajectories of 62 countries spanning the timeframe of 2000 to 2006. The findings of this research reveal a notable and intriguing pattern: an asymmetric impact of digitalization on economic growth is discerned across distinct income categories within the countries under investigation. Specifically, the study highlights a compelling distinction—while Information and Communication Technology (ICT) emerges as a catalyst for bolstering economic growth within the high and upper-middle income echelons, its contribution does not extend to fostering growth in the lower-middle income group of countries. This outcome engenders a notable shift in perspective, challenging the previously held notion that the varying levels of investment in digitalization were the primary underlying cause for sluggish growth rates observed in lower-middle developing countries. By elucidating this nuanced and complex relationship between digitalization and economic growth, the study underscores the multifaceted nature of developmental dynamics within different income strata, thereby enriching the understanding of the intricate forces at play in shaping global economic outcomes. Several other studies focus on the asymmetric impact of various determinants on economic growth. For example, Ali, et al. (2018) perform asymmetric ARDL econometric method to examine the dynamics between economic growth and overseas investment, using time series annual data from China during the period 1982-2015. Contrary to previous studies, they find empirical evidence that changes in outward foreign direct investments, both increases and decreases, have a statistically significant positive impact on economic growth in China. Chen, et al. (2020) focus on the asymmetric effects of financial development on economic growth in Kenya, over the period 1972-2017, using a model augmented with inflation and government expenditure asymmetries to inform model specification. They conclude that appropriate policies that favour low inflation and reduced government spending, expansion of feasibly reformed financial institutions, capital accumulation, and increased resource mobilization should be applied to achieve economic growth. Further, Balsalobre-Lorente, et al. (2021) find an asymmetric long-run effect of air transport on economic growth of Spain during the period 1970-2015. Lolos, Palaios and Papapetrou (2021) investigates empirically the tourism-growth relationship in Greece, over the period 1960-2020, performing a quantile regression analysis. They find that the impact of tourism remains positive across the output distribution, but the effect is more pronounced at the lower quantiles of output while at the higher quantiles of output it becomes weaker and statistically insignificant.

In contrast, within the realm of digital construction, an analogous exploration of the interplay between technological advancements and economic growth unveils a distinct narrative. While Information and Communication Technology (ICT) emerges as a potent catalyst for driving economic expansion in high and upper-middle income countries, the dynamics shift when examined through the lens of digital construction's impact on economies at different income levels. Just as in the case of ICT, digital construction's transformative potential is evidenced by its significant contribution to fostering growth in high and upper-middle income economies. However, what sets digital construction apart is its potential to transcend the previous limitations observed within the lower-middle income bracket. In contrast to the observed asymmetry in ICT's effects, digital construction presents a more equitable and inclusive paradigm by offering promising avenues for enhancing economic growth across a broader spectrum of countries, including those within the lower-middle income range. This juxtaposition underscores the nuanced and evolving nature of the relationship between technology-driven sectors like digital construction and economic progress, while also accentuating the potential for digital construction to serve as a more universally accessible driver of growth across varying income categories.

Furthermore, the research conducted by Abendin and Duan (2021) provides valuable insights into the intricate relationship between the digital economy, international trade, and Africa's economic growth. Their study encompasses an extensive dataset comprising annual panel data from 53 countries, spanning the period from 2000 to 2018. The empirical findings of their investigation unveil a compelling narrative—the digital economy assumes a pivotal role in promoting economic growth across the African continent. Particularly noteworthy is the study's revelation that international trade exhibits a synergistic relationship with the digital economy, enhancing its impact on growth. This captivating discovery underscores a crucial dynamic: the intertwined nature of digitalization and international trade as dual drivers of economic progress. Considering these findings, the authors offer a salient policy recommendation, advocating that governments prioritize the development of the digital economy as a strategic avenue for harnessing the full growth potential of international trade. This strategic alignment resonates with the research by Aghaei and Rezagholizadeh (2017), which similarly demonstrates the positive influence of digitalization on economic growth, with effects permeating both the demand and supply sides of economies. Collectively, these scholarly contributions coalesce to reinforce the imperative role of the digital economy in shaping economic trajectories, while also underscoring the symbiotic relationship it shares with international trade in driving holistic and sustainable growth (Adeleye and Eboagu, 2019; Czernich, et al., 2011; Ehigiamusoe and Lean, 2018; Nkikabahizi, et al., 2018).

In a comprehensive study by Bulturbayevich and Jurayevich (2020), the critical significance of the digital economy is delineated within the context of the Republic of Uzbekistan's growth trajectory. The authors aptly underscore the integral role of digitalization in propelling growth rates within the nation. Notably, the study highlights a pivotal realization—the process of digitizing all sectors of the economy is undoubtedly complex and challenging; however, it stands as an imperative step. The research elucidates a compelling reality: the integration of digitization is not merely advantageous but rather imperative for the Republic of Uzbekistan to forge connections and pathways into the global economy. A fundamental assertion surfaces—one that firmly establishes that without the embrace of digitization, the prospect of integrating into the world economy becomes an unattainable aspiration. Undoubtedly, the study unveils a thought-provoking conclusion, wherein it asserts that the construction sector stands among those pivotal sectors that demand comprehensive digitization. Within the broader context of Uzbekistan's growth ambitions, this finding underscores the transformative potential held within the integration of digital technologies within the construction domain. By advocating for the full digitization of the construction sector, Bulturbayevich and Jurayevich offer a prescient directive—one that resonates with the overarching theme of digitization's vital role in underpinning economic expansion. Ultimately, their research not only underscores the importance of the digital economy but also pinpoints a specific sector, construction, where digitization's infusion can potentially yield transformative outcomes for the Republic of Uzbekistan's economic trajectory.

Pradhan, et al. (2019) undertake a comprehensive exploration that delves into the intricate interconnections existing among venture capital investment, Information and Communication Technology (ICT) infrastructure, and economic growth. Anchored in a dataset comprising annual data gleaned from 25 European nations over the span of 1989 to 2016, the study unfurls a compelling narrative that underscores the existence of a robust and enduring relationship—cointegration—between these aforementioned variables.

When the focus shifts to the short-term horizon, the research unfurls a captivating revelation: a dynamic synergy unfolds among the development of ICT infrastructure, the infusion of venture capital, and the trajectory of economic growth. In most instances examined, the symbiotic relationship becomes evident as these elements interplay to reinforce each other's impact. This symbiosis within the short-term realm accentuates the interconnected nature of these key drivers, suggesting a reciprocal influence wherein the progression of ICT infrastructure and venture capital infusions catalyses and augments economic growth, and vice versa.

Ultimately, the study by Pradhan, et al. (2019) not only provides empirical validation for the existence of a long-term relationship among venture capital, ICT infrastructure, and economic growth but also unveils the intricate and mutually reinforcing dynamics at play within the short-run timeframe. These findings collectively underscore the pivotal role of technology-driven investments and infrastructure in shaping economic trajectories, offering a nuanced perspective that illuminates the interwoven fabric of progress within a technologically evolving landscape. Wang, et al. (2022) examine another important aspect of digitalizing the economy, namely the impact, among other megatrends, on transforming career management thus providing a competent approach to the labour market in Asian countries. The main conclusion of the research is that, taking for granted that Asian countries possess a highly skilled young workforce, policymakers should match educational approaches to the new digital era in order to prepare young students for the requirements and challenges of the digital economy.

Economic digitalization also affects the economic performance through the channel of tourism. Tang, Cai and Xu (2022) focus on the impact of digital economy on the urban development using the digital economy index and urban tourism development. An interesting feature of this research paper is that the authors constructed a digital index that considers digital infrastructure, digital industry development and inclusive digital finance. Their econometric methodology is based on panel threshold as well as spatial Durbin model, including a panel data sample of 284 prefecture level and above Chinese cities during the period 2011-2019. Their results are in line with the conclusion that digital economy drives urban tourism development. Further, they find geographical asymmetries as the positive impact of digitalization is more intense in mid – western, non – tourist and low – level cities of China.

Setaki and van Timmeren (2022) examine the intersection of Circular Economy, disruptive technologies and the building industry. They mention eight disruptive technologies that if integrated by the building industry can improve data management from the phase of design to fabrication and demolition. The technologies, that by definition are digital technologies, are the following: Internet of Things (IoT), Building Information Modelling (BIM), Robots, Artificial Intelligence (AI), 3D printing, Blockchain, Drones, Augmented Reality (AR). The authors note that the implementation of the above technologies is still in a preliminary phase, not practically tested and thus not yet assess when it comes to their business usefulness and viability. Ionescu-Feleagă, Ionescu and Stoica (2023) analyse the relationship between digitalization and sustainable development in the European Union (EU) countries, between 2019 and 2021, before and during the COVID-19 pandemic. Therefore, they study the correlations between Digital Economy and Society Index (DESI), on one side, and Sustainable Development Goal Index (SDG Index) and Spillover Index (SS Index), on the other side. The empirical results provide evidence in favour of a positive relationship between DESI index and SDG index, as well as geographical asymmetries with a larger effect in the Northern and Western region, while there exists a negative relationship between DESI and Spillover Index, with the latter being statistically significant only during the period 2019-20.

Rodrigo, et al. (2023) provide a review of the literature related to the use of digital technologies in the construction industry to enhance circular economy. Their sample includes 365 publications, distinguished between two main categories, namely Digitalization and advanced technologies and Sustainable and construction technologies. The two categories are further classified into eight subcategories, namely Machine learning technologies, Artificial intelligence, Deep learning, Big data analysis, Object detection and computer vision, when it comes to the former category and Internet of things, Blockchain technology and BIM for the latter category. Further, their literature review revealed nine challenged that pose important obstacles in adopting and integrating digital technologies in the construction sector (Digital Construction – DC), namely resistance to change, skills gap, implementation costs, data privacy and security concerns, lack of standardisation, limited scalability, lack of data interoperability, regulatory challenges and limited availability of data. The same conclusions are extracted by the literature review of Limna, Kraiwanit and Siripipatthanakul (2022), which states that digital economy is a powerful tool to promote economic growth and development.

Another important aspect of digitalization in the economy is privacy protection, in the sense of accountability in management of digital personal data. Therefore, countries have started, gradually, taking legal actions towards the direction of protecting citizens' rights, like the EU General Data Protection Regulation (GDPR). Rosadi, et al. (2023) evaluate the Personal Data Protection Bill introduced by the Indonesian Communication Ministry and conclude that it meets the international privacy standards.

Within the context of digital construction, the International Organization for Standardization (ISO) has introduced an influential framework known as ISO 19650. This framework is designed to revolutionize and streamline the processes involved in the management of information and data throughout the lifecycle of construction projects. ISO 19650 places a comprehensive emphasis on Building Information Modelling (BIM) and digital technologies, aiming to enhance collaboration, efficiency, and interoperability among various stakeholders within the construction industry. By establishing standardized guidelines and protocols for the organization, exchange, and utilization of digital information, ISO 19650 facilitates a seamless integration of digital tools and methodologies, ultimately fostering improved decision-making, reduced errors, and optimized project outcomes. As the construction industry increasingly embraces digitalization, ISO 19650 serves as a fundamental cornerstone, guiding practitioners towards a cohesive and standardized approach to harnessing the transformative potential of digital technologies within construction processes.

Moreover, the ICIS (2022) offers a comprehensive analysis of the current state and evolving trends in Building Information Modelling (BIM) education worldwide. This report provides valuable insights into the integration of BIM within higher education, technical training institutions, and vocational programs across diverse countries and regions, focusing on the issues of (a) Varied Implementation Levels and Sophisticated Content, (b) Multidisciplinary Approach and Vocational Training, (c) Challenges and Progress, (d) Certification and Industry Collaboration, (e) Global Pandemic Impact and Adaptation and (f) Comprehensive BIM Education. Based on the ICIS (2022) that offers a comprehensive overview of the current landscape and trends in Building Information Modelling (BIM) education worldwide aligns with the broader digital construction transformation, the report highlights the integration of sophisticated BIM elements, multidisciplinary approaches, and industry collaboration. The challenges and adaptability observed in BIM education resonate with the dynamic shift towards digital construction, where overcoming resistance, resource limitations, and standardization hurdles mirrors the journey toward embracing digital tools and methodologies in construction practices. The report's emphasis on certification and collaboration reflects the global drive to validate digital competence. Ultimately, this report serves as a valuable guide for fostering a digitally ready workforce, bridging theoretical knowledge with practical application in the digital construction era. Consequently, the prominence of technological innovation, particularly the integration of diverse technologies, underscores an equally crucial need to elevate and augment human capital.

Moreover, the pressing requirement to effectively capture real-time data streams from construction sites accentuates the indispensability of a robust connectivity infrastructure. This encompasses ensuring a seamless continuum encompassing data collection, transfer, storage, and processing operations. Moreover, the call to harness real-time data streams from construction sites underscores the critical importance of establishing resilient connectivity infrastructure. This encompasses ensuring the seamless progression of data collection, transfer, storage, and processing. Connectivity has emerged as a central driving force propelling digital construction forward, aligning seamlessly with Latham's proposition of bolstering data accuracy to minimize errors and embracing lean principles (Koskela, 1992), systematic methodologies, and agile approaches. The establishment of connectivity bridges the gap between people, processes, and technology. In essence, connectivity serves as a linchpin, propelling the construction sector closer to comprehensive digitalization, where the synergy of human expertise, streamlined processes, and cutting-edge technology converge for transformative outcomes. This symbiotic relationship between connectivity and digital construction resonates with the overarching principles of Industry 4.0, where the integration of cyber-physical systems enhances operational efficiency and innovation (Lee, Kao and Yang, 2015). Thus, by fostering connectivity, the construction industry is poised to embrace a new era of data-driven decision-making, enhanced collaboration, and optimized project outcomes. As connectivity becomes the backbone of data-driven decision-making and collaboration in construction (Kapogiannis and Sherratt, 2018), it similarly empowers the evolution of digital public services, leading to more citizen-centric, responsive, and effective governance (World Bank, 2020).

In the dynamic interplay between technological advancement and economic growth, the emergence of digital construction introduces a new dimension, potentially yielding both symmetrical and asymmetrical effects on countries' GDP. While previous research has shed light on regional disparities within the impact of the digital economy (Zhang, et al., 2022) and geographical asymmetries in digitalization's influence (Ionescu-Feleagă, Ionescu and Stoica, 2023), the present focus lies in unexplored territory—the intricate relationship between digital construction and economic development. This investigation aims to uncover possible asymmetries in the implementation of digital construction across diverse nations, pinpointing the types of countries where such disparities may arise, and proposing actionable policy measures to address them. By delving into this uncharted realm, this study presents an original inquiry into the potential asymmetrical effects of digital construction on countries' GDP growth rates, contributing to the broader understanding of the multifaceted interplay between technological evolution and economic progress.

Overall, while the existing literature delves extensively into the social and technological aspects, a comprehensive analysis of the economic contributions of digital construction to a nation's economic growth is conspicuously absent. The above literature review revealed the need for a more in-depth analysis of the linkages between construction sector and specifically Digital Construction (DC) and economic growth. It is evident that the current literature has not focus on the above relationship and the existence of possible asymmetries. Further, the review has also revealed the need to pay attention to the role of collaborative culture in mitigating the difficulties arising from the limited ability of some countries to translate digital technology into growth.

Data Statistical Properties and Econometric Methodology

In this section we examine the statistical properties of our data and then we describe the main econometric methodology that we perform in Section 5. The methodological steps that we perform are the following:

Step 1: We report the variables and the corresponding sources of the variables (Section 4.1-Table 2).

Step 2: We present and analyse the summary statistics (Section 4.1-Table 3). We conclude that we have strong evidence in favour of nonlinearities and non-normal distribution in our variables, with non-Gaussian features arising at the tails of the series.

Step 3: We conduct panel unit root tests to examine the order of integration of our variables (Section 5.1-Table 4).

Step 4: We apply cross sectional independence test and slope homogeneity tests (Section 5.1 – Table 5).

Step 5: Having detected nonlinear features in our data (Step 2) as well slope heterogeneity (Step 4), we choose to perform the Quantile via moments methodology (Machado and Santos Silva, 2019) that accounts for slope heterogeneity and offers a more robust econometric technique in the presence of conditional heterogeneity and departures from the Gaussian conditions. The econometric methodology is reported in Section 4.2 and the empirical application of it, as well as a discussion of the results are reported in Section 5.2 (Tables 6, 7).

Step 6: We provide policy implications and guidelines for practitioners (Section 6).

DATA SOURCES AND STATISTICAL PROPERTIES OF VARIABLES

The empirical investigation of the relationship between GDP growth rates and Digital Construction is carried out using panel data consisting of 27 EU countries, over the period 2017-2022[1]. Availability of DESI index (Digital Economy and Society Index) determines the empirical analysis since it is not available prior to 2017. DESI index is a composite index that summarizes relevant indicators on Europe's digital performance and tracks the evolution of EU Member States, across different dimensions: Connectivity, Human Capital, Integration of Digital Technology and Digital Public Services. Each of the dimensions are of equal importance, reflected in the equal weights of each dimension in the aggregate DESI index. The Human Capital dimension assesses both internet user skills of citizens and advanced skills of specialists. Connectivity considers both fixed and mobile broadband, with indicators measuring the supply and the demand side as wells as retail prices. Integration of Digital Technology dimension considers digital intensity, take-up of selected technologies by enterprises and e-commerce. Finally, the Digital Public Services dimension describes the demand and supply of e-government as well as open data policies. Each of the above dimensions consists of sub-dimensions[2].

1 Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

2 Human Capital sub-dimensions (weights are in parentheses): Internet user skills (50%), Advances skills and development (50%). Connectivity sub-dimensions: Fixed broadband take-up (25%), Fixed broadband coverage (25%), Mobile broadband (40%), Broadband prices (10%). Integration of digital technology sub-dimensions: Digital intensity (15%), Digital technologies for businesses (70%), e-Commerce (15%). Digital public services sub-dimensions: e-Government (100%).

Table 2 reports the variables of our model and the corresponding source for each of them. To account for the digital construction effects on GDP growth rate (GDP_g) we create a composite variable, called Digital Construction variable (DC_i), which consists of the different specifications of DESI index ($DECI_i$), as the digital proxy and Gross Fixed Capital Formation ($GFCF$), as a proxy for the construction of infrastructure activity. i denotes the different dimension of the digital construction variable, as mentioned in Table 2. To account for omitted variable bias we also use a set of control variables, which includes components of aggregate demand, namely annual % growth rate of household and NPISHs final consumption expenditure (C), annual % growth of general government final consumption expenditure (G), annual % growth of net exports of goods and services (N_x). Further, considering that both public and private investments in infrastructure are the most volatile component of the aggregate demand we introduce in our model an economic policy uncertainty variable (epu).

Table 2. Variables and Sources of Variables

Notation	Variable	Source
GDP_g	GDP growth (annual %)	World Bank national accounts data, and OECD National Accounts data files
$DECI_{agg}$	Digital Economy and Society Index, where i denotes different specifications of the DESI index: $DECI_{agg}$ (aggregate score), $DECI_{hc}$ (human capital), $DECI_{con}$ (connectivity), $DECI_{idt}$ (integration of digital technology), $DECI_{dps}$ (digital public services)	https://digital-agenda-data.eu/datasets/desi/indicators
$GFCF$	Gross fixed capital formation (constant LCU)	World Bank national accounts data, and OECD National Accounts data files
DC_i	Digital Construction, where i denotes different specifications, according to the DESI index, namely DC_{agg}, DC_{hc}, DC_{con}, DC_{idt}, DC_{dps}	$DC_i = GFCF \times DECI_i$
epu	Global Economic Policy Uncertainty	https://www.policyuncertainty.com/
C	Household and NPISHs Final consumption expenditure (annual % growth)	World Bank national accounts data, and OECD National Accounts data files
G	General government final consumption expenditure (annual % growth)	World Bank national accounts data, and OECD National Accounts data files
N_x	Net exports of goods and services (annual % growth)	World Bank national accounts data, and OECD National Accounts data files

Table 3 presents the summary statistics for the variables along with their skewness and kurtosis. Skewness is a measure of the symmetry of the probability distribution of a variables about its mean. When the value of skewness is zero, then the distribution of the variable is normal (symmetrical). According to our data, the distribution of our variables, except for the epu which is fairly symmetrical, is either moderately (DC_{agg}, DC_{hc}, DC_{idt}, DC_{dps}, N_x) or highly skewed (GDP_g, DC_{con}, C, G). Kurtosis is a measure of the tail heaviness of the distribution, as it measures the weight of the tails relative to the rest of distribution. In practical terms, kurtosis measures the outliers of the distribution. According to our data, except for the DC_{agg} variable, which exhibits mesokurtic distribution, the distribution of the rest variables is either platykurtic (DC_{hc}, epu) or leptokurtic (GDP_g, DC_{con}, DC_{idt}, DC_{dps}, C, G, N_x). Overall, we conclude that we have strong evidence in favour of nonlinearities and non-normal distribution in our variables, with non-Gaussian features arising at the tails of the series.

Table 3. Summary statistics

Variable	No. of obs.	Mean	Median	Standard Deviation	Min	Max	Skewness	Kurtosis
GDP_g	162	2.758	3.038	4.212	-11.325	13.588	-0.809	4.551
DC_{agg}	162	1062.92	1043.817	282.671	494.904	1876.253	0.427	3.021
DC_{hc}	162	285.264	280.850	64.008	175.242	441.348	0.459	2.467
DC_{con}	162	235.975	223.203	86.323	75.308	521.530	0.841	3.607
DC_{idt}	162	184.528	178.256	68.566	59.738	392.327	0.632	3.326
DC_{dps}	162	357.151	366.032	105.157	47.275	574.332	-0.480	3.163
epu	162	238.872	235.391	50.518	175.645	318.38	0.241	1.678
C	162	2.300	2.924	4.478	-12.238	11.566	-1.047	4.343
G	162	2.559	2.059	3.060	-4.282	15.791	1.252	6.091
N_x	162	-0.543	-0.745	4.637	-30.475	22.416	-0.469	18.123

ECONOMETRIC METHODOLOGY

The previous data analysis revealed the existence of possible asymmetric features in the panel which indicates the need for applying econometric techniques that allows us to examine the impact of Digital Construction not only in the mean, but across the GDP distribution. However, in order to be able to choose the proper estimation methodology, as well as the modelling specification, we must first test some additional statistical properties of our variables.

Consequently, we frame our econometric methodology as follows: First, we conduct panel unit root tests to examine the order of integration of our variables, which is of vital importance for determining the proper modelling specification. Second, we apply cross sectional independence test and slope homogeneity tests, which will determine the econometric technique that we will apply. Third, considering the results of the data analysis as well as the unit root tests and the cross sectional and slope homogeneity tests, we apply the quantile via moments methodology of Machado and Santos Silva (2019), by developing a location – scale model of the following form:

$$GDP_{g_{it}} = a_{it} + X_{it}'\beta + (\delta_i + Z_{it}'\gamma)U_{it} \tag{1}$$

where $\Pr\{\delta_i + Z_{it}'\gamma > 0\} = 1$ and $(a_i, \delta_i), i = 1, \dots, n,$ capture the individual i fixed effects and Z is vector of known differentiable transformations of X. The sequence $\{X_{it}\}$ is strictly exogenous, i.i.d for any fixed i and independent across i and denotes a vector of the independent variables, among the Digital Construction (DC_i) and its dimensions as well as the control variables, U_{it} are i.i.d., statistically independent t of X_{it} and normalized to satisfy that $E(U) = 0$ and $E(|U|) = 1$. Given the above assumptions, equation (1) gives that:

$$Q_{GDP_g}(\tau/DC_{it}) = \left(a_i + \delta_i q(\tau)\right) + X'_{it}\beta + Z'_{it}\gamma q(\tau) \quad (2)$$

In equation (2) the quantile – τ fixed effect for individual i is given by the coefficient $a_i(\tau) \equiv a_i + \delta_i q(\tau)$ and can be estimated as follows:

$$\widehat{a}_i(\tau) = \frac{1}{\mathrm{T}}\sum_{t=1}^{T}(GDP_{g_{it}} - X'_{it}\widehat{\beta}) + \widehat{q}\,\frac{1}{T}\sum_{t=1}^{T}\left(\left|\widehat{R_{it}}\right| - Z'_{it}\widehat{\gamma}\right) \quad (3)$$

where, R denote the estimated residuals $\hat{R}_{it} = GDP_{g_{it}} - \hat{a}_i - X'_{it}\hat{\beta}$. It should be noted that in our empirical analysis we use alternative specifications of the above model with respect to the use of the dependent and the independent variables.

The main advantages of the above methodology are the following: First, in general, quantile regression analysis provides a more comprehensive description of the conditional distribution than the ordinary mean approach and it offers a more robust econometric technique in the presence of conditional heterogeneity and departures from the Gaussian conditions as in Palaios and Papapetrou (2019) and Lolos, Palaios and Papapetrou (2023). Second, the quantile via moments methodology accounts for possible cross-sectional dependence and slope heterogeneity as well. Finally, the main advantage of this methodology is that it allows the use of methods that are only valid in the estimation of conditional means, while still providing information on how the regressors affect the entire conditional distribution (Machado and Santos Silva, 2019).

Empirical analysis and discussion

The empirical analysis is structured as follows: The initial phase encompasses preliminary findings, entailing unit root tests, cross-sectional independence assessments, and slope homogeneity tests. Subsequently, the focus transitions to the core analysis, where the quantile via moments econometric technique is employed to delve into the main investigation. This structured approach enables a comprehensive exploration of the research objectives, culminating in a nuanced understanding of potential asymmetries in the relationship between digital construction and GDP growth rates.

PRELIMINARY RESULTS

To examine the stationarity properties of our variables, which allow to choose the proper model specification, we apply the Fisher type (P-Perron) unit root test and the Hadri LM stationarity test. The results are presented in table 4. The former unit root test assumes as the null hypothesis that the panels include a unit root (non-stationary data). Fisher-type tests approach testing for panel-data unit roots from a meta-analysis perspective, namely they conduct unit-root tests for each panel individually and then combine the p-values from these tests to produce an overall test. To mitigate the impact of possible cross-sectional dependence we follow Levin, Lin and Chu's (2002) procedure which, for each time period, computes the mean of the series across panels and subtracts this mean from the series. The null hypothesis of non-stationarity is rejected in all cases. Next, we apply the Hadri (2000) LM test which assumes as the null hypothesis that all the panels are stationary. According to Hadri (2000) the classical hypothesis testing requires strong evidence to the contrary to reject the null hypothesis. Therefore, the advantage of his tests is that the null and alternative hypotheses are reversed, which allows to test the validity of the results of the Fisher-type P-Perron test that was conducted under the null hypothesis of non-stationarity. In addition, the Hadri LM test requires that the panels be strongly balanced, an assumption which perfectly fits our data. Our results show that we cannot reject the null hypothesis of stationarity. Therefore, we have strong evidence that our data is characterized by constant properties (mean reversion), namely it is stationary.

Table 4. Panel data unit root tests

Variable	Fisher type (P-Perron) test	Hadri LM stationarity test
GDP_g	71.827*	-0.374
DC_{agg}	203.441***	1.057
DC_{hc}	187.788***	-0.465
DC_{con}	57.467	0.966
DC_{idt}	358.685***	2.450*
DC_{dps}	89.8896 ***	0.311
epu	15.4395	-0.1935
C	132.780***	0.593
G	280.547***	0.964
N_x	100.603***	-2.061

Notes: P values are in parentheses. *, **, *** denote significance at 10%, 5% and 1% level, respectively.

The subsequent stage involves the execution of cross-sectional independence tests, aimed at scrutinizing the hypothesis asserting the independence of error terms across diverse cross-sectional units. This step constitutes a crucial component of the analytical process, contributing to the rigorous evaluation of the research framework and its underlying assumptions.

According to Chudik and Pesaran (2013) ignoring cross-sectional dependence of errors leads to serious consequences while the empirical experience shows that cross sectional dependence in economics in usually the rule rather than the exception. On the issue of the causes of cross-sectional dependence, De Hoyos and Sarafidis (2006) mention that it may be due to the presence of common shocks and unobserved components that become part of the error term. When it comes to the negative effects of a possible interdependence among the error terms of cross-sections, Phillips and Sul (2003) state that they may lead to a decrease in estimation efficiency. While Breusch and Pagan (1980) test is valid in cases of panel data with large time periods and small number of cross sections, it is inappropriate in the context of small time periods and large sections, as it holds in our case. Therefore, to account for the above-mentioned issues, we choose to perform two semi-parametric cross sectional independence tests, namely the Friedman (1937) test and the Frees (1995) test. Both of them assume cross-sectional independence as the null hypothesis. Our results, reported in the second and third column of table 5, show that the null hypothesis of cross-sectional interdependence cannot be rejected.

Further, we test for slope homogeneity. In the case of a model that consists of heterogeneous slopes, imposing slope homogeneity yields inconsistent and biased results. We perform a test that is a standardized version of Swamy's (1970) test for slope homogeneity presented by Pesaran and Yamagata (2008). A main advantage of the test is that it can be used for both balanced and unbalanced panels. The null hypothesis of the model assumes slope homogeneity across cross-sectional units, namely the slope coefficients are identical. It should be noted that we use the specification of the heteroskedasticity and autocorrelation consistent (HAC) test statistic of Blomquist and Westerlund (2013) and in addition, following Andrews and Monahan (1992), we also perform prewhitening to reduce small-sample bias in HAC estimation. Our results, reported in the fourth column of table 5, show that, in all cases, the null hypothesis of slope homogeneity is rejected.

Table 5. Cross sectional independence test and slope homogeneity test

Variable	Cross sectional independence		Slope homogeneity
	Friedman test	Frees test	Pesaran and Yamagata test
Specification: Aggregate	17.392 (0.402)	0.187 (0.402)	8.117***
Specification: Human capital	13.392 (0.408)	0.239 (0.408)	4.731***
Specification: Connectivity	14.471 (0.399)	0.280 (0.399)	15.907***
Specification: Integration of digital technology	19.889 (0.419)	0.684** (0.419)	6.384***
Digital public services	17.836 (0.404)	0.479* (0.404)	12.198***

Notes: Average absolute values of the off-diagonal elements are in parentheses of the cross-sectional independence tests. *, **, *** denote significance at 10%, 5% and 1% level, respectively.

MAIN RESULTS: QUANTILES VIA MOMENTS ANALYSIS

Having detected the nonlinear features of our data (section 4.1), it becomes essential to perform an econometric technique that provides a more comprehensive description of the conditional distribution than the ordinary mean approach. Further, as it is evident from the Pesaran and Yamagata (2008) test, the null hypothesis of slope homogeneity is rejected in all cases. Therefore, we choose to perform the Quantile via moments methodology (Machado and Santos Silva, 2019) that account for slope heterogeneity and offers a more robust econometric technique in the presence of conditional heterogeneity and departures from the Gaussian conditions.

Tables 6 present the estimation results for the specification of the aggregate Digital Construction (DC_{agg}) variable, with fixed effects. The first column shows the specification of our model when it comes to the independent variables. Column 2 displays the estimates of the parameters in the location function (mean approach). Columns (3) – (11) show the estimated coefficients for each quantile. Following Lolos, Palaios and Papapetrou (2021), we categorize the quantiles into threes regimes, namely a bearish economy [τ = (0.10, 0.20, 0.30)], a normal economy [τ = (0.40, 0.50, 0.60)] and a flourishing economy [τ = (0.70, 0.80, 0.90)]. According to our results for the aggregate Digital Construction (DC_{agg}) variable we observe that its impact on GDP growth rates is positive and statistically significant along the entire conditional distribution. We also find evidence that the impact of the DC_{agg} variable increases in absolute terms as we move from the lower (bearish economy) to the upper (flourishing economy) quantiles. Specifically, in the case of a bearish economy the quantile coefficients of Digital Construction are $Q_{DC_{agg}}$ = (0.0353, 0.0402, 0.0428), in the case of normal economy the quantile coefficients are $Q_{DC_{agg}}$ = (0.0458, 0.0485, 0.0519) and in the case of a flourishing economy the coefficients are $Q_{DC_{agg}}$ = (0.0546, 0.0569, 0.0604). Further, the signs of the rest control variables are as expected. The impact of *epu* variable, representing economic policy uncertainty, is negative indicating that, as expected, higher economic policy uncertainty is associated with lower GDP growth rates. As expected, the coefficients of private final consumption expenditure, C and government spending, G, and net exports, N_x indicate a positive impact on GDP growth rates.

Table 7 presents the estimation results for the rest specifications (subdimensions) of the Digital Construction variable. Each specification explores the relationship between different dimensions of Digital Construction (DC) and various economic indicators across different quantiles of the GDP distribution. The estimated coefficients of the dimensions follow the same path, namely there are positive and their impact increases as we move from a bearish to a flourishing economy. In addition, we observe that the most influential Digital Construction subdimension is that of the Human Capital (DC_{hc}), which signals the need for more investments in the human factor to be able to integrate digital construction techniques in developing infrastructure. Specifically, when it comes to the impact of the dimension of Human Capital the data suggests that as the level of DC_{hc} increases there is a positive, statistically significant and more pronounced impact on GDP growth rates. This implies that investing in human skills and capabilities within the construction industry, which is the Human Capital component of DC, is associated with higher economic growth rates across different economic conditions. For the dimension of Connectivity, *DC_con*, similar trends emerge, where higher levels of *DC_con* in the construction sector are associated with increased GDP growth rates, particularly in higher quantiles. This indicates that advancements in connectivity through digital construction techniques contribute positively to economic growth, especially in more favourable economic conditions. The analysis of Integration of Digital Technology, *DC_idt*, also reveals a positive impact on GDP growth rates across quantiles, reinforcing the importance of adopting digital technologies in construction for sustained economic expansion. Lastly, in terms of Digital Public Services the data showcases that, higher levels of *DC_dps* are linked to increased GDP growth rates, particularly in the upper quantiles. This suggests that embracing digitalization in public services within the construction sector can contribute positively to economic growth, especially during more prosperous economic periods.

The study's findings align with the seminal work of Yousefi (2011), whose comprehensive examination encompassed 62 countries during the 2000-2006 timeframe. Notably, Yousefi's analysis revealed an intriguing pattern—a nuanced and asymmetric correlation between digitalization and economic growth across distinct income strata. High and upper-middle income economies exhibited a notable positive correlation between Information and Communication Technology (ICT) adoption and economic growth, whereas such a correlation was notably absent in lower-middle income countries. The interpretation of the above findings according to Yousefi (2011) is that the level of investment in digitalization is not the cause of slow growth in lower-middle developing countries as previously thought, because it fails to contribute to the growth of the lower-middle income group countries.

Yet, an alternative interpretation emerges within the current study's framework, a perspective congruent with the viewpoints endorsed by a majority of scholars (Pradhan, et al., 2019; Setaki and van Timmeren, 2022; Wang, Liu and Li, 2022; Tang, He and Hong, 2022). This outlook contends that digitalization's potential to stimulate growth extends even to economies characterized by lower income levels. This potential, however, hinges on the implementation of strategic measures that adeptly harness its beneficial economic impacts (Adeleye and Eboagu, 2019; Czernich, et al., 2011; Ehigiamusoe and Lean, 2018; Nkikabahizi, et al., 2018). Consequently, the observed attenuated coefficient reflecting digitalization's influence on economic growth need not signify an intrinsic incapacity to drive expansion. Rather, it serves as an indicator prompting nations with subdued growth rates to institute targeted structural reforms. These reforms, aimed at optimizing digitalization's integration, hold the promise of unleashing its full potential to invigorate growth trajectories. This revaluation underscores the paramount importance of proactive policy interventions tailored to extract the transformative potential of digitalization, guiding countries toward a path of robust and equitable economic progress.

The significance of these findings unfolds on a dual plane. Initially, they underscore a pivotal realization—the potential benefits of Digital Construction are more pronounced within robust economies, accentuating the imperative for targeted interventions to bolster technology integration in weaker economies (Zhang, et al., 2022; Ionescu-Feleagă, Ionescu and Stoica 2023). This clarion call for practical solutions emerges as a strategic imperative, aiming to enhance the pace of digital technology assimilation within the construction domain of economically challenged nations. Moreover, the results carry profound implications on a secondary level. They illuminate a pathway characterized by positive outcomes stemming from digital reforms, advanced technology adoption, fortified digital infrastructure, and heightened investments in human capital (Pradhan, et al., 2019; Bulturbayevich and Jurayevich, 2020; Setaki and van Timmeren, 2022). These affirmative dynamics are poised to exert a dominant influence, amplifying the developmental trajectory of already established economies. The cumulative effect is poised to usher in a phase of heightened development, bolstered by the synergistic interplay of these transformative factors (Wang, Liu and Li, 2022; Tang, He and Hong, 2022).

In summary, the empirical results underscore the positive association between various dimensions of DC and GDP growth rates across different economic conditions. This emphasizes the importance of ongoing innovation and integration of digital technologies in the construction industry to foster sustained economic expansion and capitalize on the benefits of digitalization. Further, our findings underscore Digital Construction's potential, advocating tailored integration strategies in less developed economies. Hence, the research underscores the significant role of Digital Construction in influencing GDP growth rates across different economic conditions. The study's findings advocate for tailored interventions to bolster technology integration in less developed economies while highlighting the potential for enhanced growth through advanced digital reforms. The positive outcomes resulting from technology adoption, fortified digital infrastructure, and investments in human capital offer a dual pathway—one for the development of weaker economies and another for the amplification of already established ones. These dynamics hold the promise of ushering in a phase of heightened and equitable economic progress, propelled by the synergistic interplay of transformative factors.

Table 6. Estimation results (Quantiles via Moments) for the aggregate Digital Construction (*DC_agg*) index, with fixed effects. Dependent variable is GDP_g.

	Mean approach	Bearish economy			Normal economy			Flourishing economy		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	location	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
DC_{agg}	0.0485***	0.0353**	0.0402***	0.0428***	0.0458***	0.0485***	0.0519***	0.0546***	0.0569***	0.0604***
	(0.0011)	(0.0014)	(0.0012)	(0.0011)	(0.0011)	(0.0011)	(0.0012)	(0.0012)	(0.0013)	(0.0014)
epu	-0.0230***	-0.0229***	-0.0229***	-0.0230***	-0.0230***	-0.0230***	-0.0230***	-0.0230***	-0.0230***	-0.0231***
	(0.0041)	(0.0055)	(0.0048)	(0.0041)	(0.0042)	(0.0041)	(0.00423)	(0.0044)	(0.0046)	(0.0051)
C	0.599***	0.684***	0.652***	0.636***	0.617***	0.599***	0.577***	0.560***	0.545***	0.523***
	(0.0581)	(0.0704)	(0.0622)	(0.0616)	(0.0599)	(0.0590)	(0.0596)	(0.0612)	(0.0622)	(0.0669)
G	0.0984	0.0694	0.0801	0.0859	0.0925	0.0985	0.106*	0.112*	0.117*	0.125
	(0.0601)	(0.0648)	(0.0599)	(0.0592)	(0.0591)	(0.0603)	(0.0636)	(0.0670)	(0.0704)	(0.0777)
N_x	0.215***	0.209***	0.212***	0.213***	0.214***	0.215***	0.217***	0.218***	0.219***	0.220***
	(0.0454)	(0.0408)	(0.0412)	(0.0421)	(0.0436)	(0.0454)	(0.0482)	(0.0507)	(0.0530)	(0.0571)
Cons.	1.585**	1.097	1.278*	1.374*	1.485**	1.587**	1.714**	1.811**	1.898**	2.028**
	(0.670)	(0.882)	(0.764)	(0.714)	(0.678)	(0.671)	(0.697)	(0.739)	(0.793)	(0.880)
Obs.	162	162	162	162	162	162	162	162	162	162

Notes: Robust standard errors in parentheses. *, **, *** denote significance at 10%, 5% and 1% level, respectively.

Table 7. Estimation results (Quantiles via Moments) for the subcomponents of DESI index, with fixed effects. Dependent variable is GDP_g.

	location	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
Specification: Human Capital										
DC_{hc}	0.0481***	0.0344*	0.0395**	0.0427***	0.0452***	0.0482***	0.0518***	0.0546***	0.0571***	0.0611***
epu	-0.0201***	-0.0209***	-0.0206***	-0.0204***	-0.0202***	-0.0201***	-0.0198***	-0.0197***	-0.0195***	-0.0193***
C	0.634***	0.694***	0.672***	0.658***	0.647***	0.633***	0.618***	0.605***	0.594***	0.576***
G	0.102*	0.119*	0.113*	0.109*	0.106*	0.102*	0.0979	0.0945	0.0914	0.0865
N_x	0.224***	0.223***	0.223***	0.223***	0.224***	0.224***	0.224***	0.224***	0.224***	0.224***
Cons.	-7.778**	-5.556	-6.378*	-6.903**	-7.297**	-7.790**	-8.369**	-8.820**	-9.229**	-9.878**
Specification: Connectivity										
DC_{con}	0.0091***	0.0061**	0.0073***	0.0079***	0.0085***	0.0091***	0.0098***	0.0105***	0.0112***	0.0117***
epu	-0.0198***	-0.0199***	-0.0198***	-0.0198***	-0.0198***	-0.0198***	-0.0198***	-0.0197***	-0.0197***	-0.0197***
C	0.619***	0.701***	0.669***	0.654***	0.637***	0.619***	0.599***	0.582***	0.563***	0.547***
G	0.116*	0.0712	0.0883	0.0967*	0.106*	0.115*	0.126*	0.136*	0.146*	0.154*
N_x	0.214***	0.207***	0.210***	0.212***	0.213***	0.214***	0.216***	0.218***	0.219***	0.221***
Cons.	3.719***	2.622***	3.045***	3.253***	3.474***	3.712***	3.983***	4.213***	4.463***	4.670***
Specification: Integration of Digital Technology										
DC_{idt}	0.0207***	0.0112	0.0146**	0.0164***	0.0188***	0.0207***	0.0232***	0.0247***	0.0273***	0.0296***
epu	-0.0212***	-0.0198***	-0.0203***	-0.0206***	-0.0209***	-0.0212***	-0.0216***	-0.0218***	-0.0222***	-0.0225***
C	0.620***	0.708***	0.677***	0.660***	0.638***	0.620***	0.597***	0.583***	0.559***	0.538***
G	0.0821	0.0843	0.0835	0.0831	0.0825	0.0821	0.0815	0.0812	0.0806	0.0801
N_x	0.217***	0.209***	0.212***	0.214***	0.216***	0.217***	0.220***	0.221***	0.223***	0.225***
Cons.	2.489***	1.946**	2.138***	2.244***	2.381***	2.490***	2.633***	2.718***	2.870***	3.000***
Specification: Digital Public Services										
DC_{dps}	0.0152***	0.0103**	0.0121***	0.0130***	0.0141***	0.0152***	0.0166***	0.0174***	0.0184***	0.0193***
epu	-0.0223***	-0.0213***	-0.0217***	-0.0218***	-0.0221***	-0.0223***	-0.0226***	-0.0228***	-0.0230***	-0.0232***
C	0.612***	0.704***	0.669***	0.653***	0.633***	0.611***	0.586***	0.570***	0.552***	0.534***
G	0.0890	0.0825	0.0850	0.0861	0.0875	0.0891	0.0909	0.0920	0.0933	0.0946
N_x	0.219***	0.216***	0.217***	0.217***	0.218***	0.219***	0.220***	0.220***	0.221***	0.221***
Cons.	1.150	0.694	0.869	0.947	1.048	1.158	1.281	1.361	1.450	1.540
Obs.	162	162	162	162	162	162	162	162	162	162

Notes: Robust standard errors in parentheses. *, **, *** denote significance at 10%, 5% and 1% level, respectively.

Policy implications and Guidelines for Practitioners

In an era marked by the relentless march of technological progress, the role of digital technologies in shaping economic landscapes has become increasingly profound. At the forefront of this transformative wave stands Digital Construction (DC), an innovative fusion of cutting-edge digital tools and traditional construction practices. As nations strive to foster sustainable growth, enhance infrastructure, and navigate the complexities of global challenges, an intricate web of policy implications emerges from the examination of DC's impact on GDP growth rates. The empirical analysis undertaken herein reveals a captivating narrative: a resounding and statistically significant correlation between DC and GDP growth across the entire spectrum of economic conditions. This compelling finding unveils a remarkable constancy in the influence of DC, steadfastly bolstering economic growth irrespective of prevailing circumstances—be they subdued, stable, or soaring. Such a revelation not only reinforces prior research positing a symbiotic relationship between digital technologies and economic progress but also beckons policymakers to contemplate profound ramifications for future development strategies. This observation is in line with previous research that has shown a positive relationship between digital technologies and economic growth (Aghaei and Rezagholizadeh, 2017; Pradhan, et al., 2019; Zhang, et al., 2021).

Yet, the story gains complexity as the economic journey traverses diverse quantiles, each reflecting distinctive degrees of prosperity. Herein lies the revelation that the transformative impact of DC on GDP growth burgeons with the ascent from lower to upper quantiles—a testament to the amplification of its efficacy with economic improvement. This echoes akin observations in the literature, where digitalization's fruits tend to ripen more profoundly amidst the flourishing vistas of burgeoning economies. As the economy transitions from lower quantiles (reflecting less favourable economic conditions) to upper quantiles (indicative of more favourable economic conditions), the impact of DC on GDP growth becomes increasingly pronounced. This indicates that the positive effect of DC on economic growth strengthens as the overall economic situation improves. Similar findings have been reported in the literature, where the benefits of digitalization tend to amplify as economies progress (Limna, Kraiwanit and Siripipatthanakul 2022; Machado and Santos Silva, 2019). This result implies that stronger economies can use more efficiently the benefits of the Digital Construction compared to the weaker economies, thus signalling the need of the latter for practical solutions, to improve the integration rate of digitalization in the construction sector.

As this exploration delves deeper, a luminary amidst the diverse dimensions of DC comes to the fore: The Human Capital component, which stands out as the most influential. The singular impact of this facet underscores the pivotal role played by the development of human skills and acumen in effectively embedding digital construction techniques within the tapestry of infrastructure advancement. A resounding message resonates—an investment in honing the expertise of individuals within the construction domain emerges as the bedrock upon which the edifice of digitalization's benefits is erected. This resonates harmoniously with the wisdom of Koskela (1992), who eloquently articulated the centrality of human factors in the context of novel production paradigms. Recent scholarly endeavours further underscore the pressing significance of continuous skills development within the digital epoch. This finding underscores the critical role of investing in human skills and capabilities to effectively incorporate digital construction techniques into infrastructure development. The implication is that nurturing and enhancing the expertise and knowledge of individuals within the construction industry plays a pivotal role in leveraging the benefits of digitalization for economic growth. This aligns with the argument made by Koskela (1992) regarding the importance of human factors in the context of new production philosophies, as well as recent studies emphasizing the significance of skills development in the digital era (Setaki and van Timmeren, 2022; Wang, et al., 2022).

Against this backdrop, a probing question resounds—does the tapestry of innovation warrant incessant weaving? The mosaic of evidence woven from this study emphatically nods in affirmation, beckoning forth the imperative of ceaseless innovation, particularly within the realm of digital construction and its intricate dance with economic growth. The rationale for perpetuating innovation finds firm ground on a series of 7 pillars (Figure 1) that could beckoning governments to embrace the digital frontier in governance strategies. These are:

a. Promoting Innovation for Sustainable Economic Growth: Policymakers should recognize the consistent and significant impact of Digital Construction (DC) on GDP growth rates. To sustain economic expansion,

Figure 1. Seven Pillars Guiding Policy Implications for Digital Construction"

governments and industries should prioritize investments in research, development, and innovation within the digital construction sector. This could involve funding research projects, supporting startups, and facilitating collaboration between academia, industry, and government agencies.

b. Investment in Human Capital Development: Given the central role of the Human Capital subdimension in driving the impact of DC on economic growth, policymakers should emphasize the importance of continuous skill development, education, and training in the construction industry. Developing and nurturing a skilled workforce equipped with digital competencies will be crucial for effective integration of digital construction techniques.

c. Fostering Digital Inclusion and Government Innovation: To maximize the benefits of digitalization, governments need to innovate their digital strategies and ensure inclusive access to digital tools and services. Policymakers should develop and implement policies that promote digital inclusion, support digital literacy programs, and create an enabling environment for the adoption of digital construction technologies by various segments of society.

d. Capitalizing on Global Megatrends: Policymakers should recognize the influence of global megatrends, such as the digital economy and challenges like the COVID-19 pandemic. They should proactively adapt policies to align with these trends and leverage opportunities for growth and innovation. This could involve creating agile regulatory frameworks and providing incentives for businesses to adopt and integrate digital construction techniques.

e. Integration of Circular Economy Principles: The intersection of the circular economy with digitalization in the building industry presents a unique opportunity for sustainable growth. Policymakers should encourage the integration of circular economy principles into digital construction practices, promoting resource efficiency, reduced waste, and environmental sustainability.

f. Supporting Infrastructure Development: Continuous innovation in digital construction techniques is essential for enhancing infrastructure development and meeting the demands of a rapidly evolving global landscape. Policymakers should prioritize investments in smart and resilient infrastructure and create regulatory environments that facilitate the adoption of advanced digital technologies in construction.

g. Public Service Enhancement: Governments should innovate their digital government strategies to enhance public services and improve efficiency. Policymakers should collaborate with relevant stakeholders to develop and implement digital solutions that streamline processes, enhance transparency, and improve service delivery in the construction and infrastructure sectors.

Conclusions. So, do we need to keep innovating?

The findings of this study emphasize the ongoing need for innovation in the context of digital construction and its impact on economic growth. Continual innovation is crucial for several reasons, as supported by various scholarly works mentioned in our study. In the contemporary landscape of technological advancement, the symbiotic relationship between Digital Construction (DC) and economic growth resonates as a beacon of progress. This connection is vividly illustrated by the consistent and statistically significant impact of DC on GDP growth rates, reinforcing the potential for innovation in this domain to underpin sustained economic expansion. However, the impact of DC on economic growth is asymmetric. As economic conditions ascend toward prosperity, the mounting influence of DC on GDP growth magnifies, beckoning forth the imperative of continuous innovation to fully unlock the transformative potential of digital technologies. This result implies that stronger economies can use more efficiently the benefits of the Digital Construction compared to the weaker economies, thus signalling the need of the latter for structural reforms, to improve the integration rate of digitalization in the construction sector. It also advocates for tailored interventions to bolster technology integration in less developed economies while highlighting the potential for enhanced growth through advanced digital reforms. The positive outcomes resulting from technology adoption, fortified digital infrastructure, and investments in human capital offer a dual pathway—one for the development of weaker economies and another for the amplification of already established ones. Amidst this intricate tapestry, the prominence of Human Capital emerges as a central theme—highlighting the pressing need for perpetual innovation in skill development, education, and training. By cultivating human capabilities and facilitating the seamless integration of digital construction techniques, innovation in this dimension emerges as a linchpin for catalysing progress (Kapogiannis and Sherratt, 2018; Setaki and van Timmeren, 2022).

Additionally, the convergence of the circular economy with digitalization within the construction realm beckons innovative approaches that harmonize sustainability aspirations with technological progress, propelling the industry towards a more resilient and environmentally conscious future. As the foundation of infrastructure development shifts to meet the demands of an ever-evolving global landscape, ongoing innovation in digital construction techniques stands as an imperative for both enhancing infrastructure and maintaining competitiveness (UNEP, 2022). The journey towards public service enhancement and effective digital inclusion follows a similar course, necessitating a continual evolution of digital government strategies to optimize service delivery and societal engagement (World Bank, 2020).

The narrative woven by the intricate interplay of DC, innovation, and economic growth forms a tapestry of progress. The symphony of sustained expansion, optimization of digitalization, nurturing of human capital, adaptation to megatrends, fusion of sustainability, fortification of infrastructure, and augmentation of public services underscores the enduring role of innovation. Guided by these resonant principles, policymakers and stakeholders are poised to shape a dynamic and prosperous future by fostering a culture of unceasing innovation in the realm of digital construction. To ensure the continued positive impact of DC on economic growth, stakeholders must prioritize ongoing innovation and investment in human capital. Sustained efforts in research, development, and implementation of cutting-edge digital construction technologies will be essential to drive economic growth, enhance productivity, and remain competitive in a rapidly changing world, especially in countries characterized by lower economic performance.

Finally, the findings of this study fill a significant research gap in literature by highlighting the importance of digital construction led growth asymmetries, namely the need of weaker countries to promote structural reforms and enduring innovation in order to improve the integration rate of digitalization in the construction sector, and thus to achieve a higher economic growth. Policymakers must prioritize investments in research, human capital development, inclusive digital strategies, and alignment with global trends to ensure sustained economic expansion, maximize the benefits of digitalization, and address emerging challenges. By fostering a culture of innovation, collaboration and enabling the integration of digital construction techniques, economies can position themselves for continued growth and competitiveness in an ever-changing world.

AUTHOR CONTRIBUTIONS

The authors have equally contributed to all parts of this paper. All the authors have read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The data employed in this research paper and the codes to replicate the results are available upon request.

DECLARATIONS

CONSENT FOR PUBLICATION

This study presents original material that has not been published elsewhere.

DISCLOSURE STATEMENT

The authors declare that they have no competing interests, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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