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DIGITALIZATION AND CONFIGURATIONAL EFFECTS ON REGIONAL INCOME INEQUALITY: ANALYSIS OF PANEL DATA FROM 134 ECONOMIES

Shuigen HU, Yulong JIE✉, Siling ZHU

School of Public Affairs, Zhejiang University, Hangzhou, China

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Abstract. The literature on the impact of digitalization on regional income disparities is fragmented and contentious. Drawing on complex systems perspective and configurational theory, this paper analyses the configurational effects of digitalization factors embedded in specific contexts on regional income disparities, using a sample of 134 economies from 2012 to 2021, employing Panel Fuzzy-Set Qualitative Comparative Analysis (Panel fsQCA) and Necessary Condition Analysis (NCA). This paper identifies four context-specific configurational patterns through which digitalization reduces regional income disparities. While no single condition emerges as a strictly necessary condition, digital inclusion and digital finance demonstrate broad positive effects across configurations. Although digital transformation cannot guarantee reduced disparities, severe digital deficiency consistently leads to widening regional income disparities. At the same time, this paper discovers previously unnoticed causal mechanisms and captures the dynamic trends and spatial characteristics of digitalization's impact. These findings offer diverse, adaptable insights for regional common prosperity.

Keywords: digitalization, regional income disparities, complex systems perspective, Panel fsQCA, NCA.

JEL Classification: O18, O33, P36, P50, R11.

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✉Corresponding author. E-mail: ***jieylvia@gmail.com***

1. Introduction

Geographic and sustainability sciences frequently highlight regional inequality as a critical research area (Fu et al., 2022). In particular, regional income inequality is closely related to socio-political conflicts and significantly impact sustainability objectives and human welfare (Wei, 2015; Ballas et al., 2017). While global initiatives have attempted to reduce poverty across developing nations, income gaps within contemporary economies continue to persist (Eva et al., 2022; Suhrab et al., 2024). The ongoing digital revolution – characterized by the rapid development of wireless connectivity solutions, distributed computing infrastructures, artificial intelligence, and other emerging computational innovations – has become increasingly embedded within socioeconomic frameworks, altering our living patterns, work methodologies, and communication approaches (Autio et al., 2021). However, as Feldman (2022) points out, digitalization may regional inequality. For example, while tech hubs thrive,

many regions are left behind due to unequal access to digital infrastructure, exacerbating income disparities. Despite widespread policy efforts to combat income disparities, many policymakers are uncertain about which specific dimensions of digitalization – such as digital finance solutions for underserved populations or e-governance innovations – offer the most robust route to reducing regional income gaps. Particularly, stakeholders such as national and local governments, and international organizations urgently seek effective strategies to harness digital tools for balanced regional development.

An increasing number of scholars are exploring various dimensions of digitalization, such as digital technology, digital infrastructure, digital economy, digital industries, digital finance, and digital governance, which independently influence regional income disparities in a linear fashion (Ding & Kang, 2024; Löfving et al., 2022; Ramadani et al., 2022; Si, 2023; Xu et al., 2023). However, substantial controversies are evident in existing ideas and findings (Haefner & Sternberg, 2020). Certain empirical research indicate that digitalization contributes to reducing regional economic differences (Bandyopadhyay & Sattarzadeh, 2010; Celbis & de Crombrugghe, 2018; Ding & Kang, 2024; Si, 2023), while others find that digitalization may actually accelerate the widening of these disparities (Deng et al., 2023; Florida & Mellander, 2016; Ramadani et al., 2022; Wang et al., 2024; Wouterlood, 2015). This simultaneous narrowing and widening of disparities through digital means has been termed the "paradoxical geographies of digitalization" (Moriset & Malecki, 2009). Furthermore, some studies reveal a more complex relationship among digital transformation, contexts, and regional disparities (Chatterjee & Turnovsky, 2012; Chen & Wu, 2021; Huang, 2021). An emerging scholarly consensus suggests that digitalization's impact on regional disparities exhibits multiple facets, mixed outcomes, and non-linear patterns, shaped by intricate interactions between various digital elements and their implementation contexts (Bauer, 2018; Liu et al., 2024; Mim & Jeguirim, 2022; Moriset & Malecki, 2009; Richmond & Triplett, 2018; Siregar, 2020; Venables, 2001; Wang et al., 2024).

Meanwhile, most studies focus on subnational regions within specific economies, such as Europe, China, and India (Consoli et al., 2023; Das & Chatterjee, 2023; Lv et al., 2022), with few encompassing large samples across diverse economies. And researchers have generally overlooked disruptions caused by economic shocks, such as the COVID-19 pandemic since 2020, resulting in findings that are far from conclusive. Furthermore, although some research employs Qualitative Comparative Analysis (QCA) to address these gaps, their approaches often neglect longitudinal dynamics and contextual dimensions, thereby failing to capture the evolving nature of digital transformation within multifaceted environments (Hou & Xiong, 2023; Yu et al., 2023). Some scholars advocate for expanded longitudinal investigations into how digital processes affect territorial inequalities over extended time periods (Liu et al., 2024).

Overall, although a substantial body of research has examined individual digital factors and their impact on regional income disparities, these studies typically treat these factors in isolation or assume linear relationships. This approach may overlook the complex interactions among multiple digital elements and their operational environments, leading to one-sided and sometimes contradictory explorations of underlying theories and mechanisms. This paper takes a critical step to address these shortcomings. Specifically, the primary question we tackle is: How do digital factors combine under contextual influences to affect changes (particularly reductions) in regional income disparities?

Based on a complex systems perspective and configurational theory, this study constructs a configurational analytical framework and conducts configurational causal analysis using

Panel fuzzy-set Qualitative Comparative Analysis (Panel fsQCA) and Necessary Condition Analysis (NCA), with a sample of 134 economies worldwide from 2012 to 2021. The complex systems perspective posits that economic systems possess complex characteristics such as multiple equilibria, path dependence, unpredictability, and asymmetry (Arthur, 2018) . The configurational approach considers how different conditions or variables combine in specific arrangements to influence outcomes. This perspective acknowledges that different combinations may produce identical results (equifinality), while similar conditions might generate divergent outcomes depending on their specific arrangement (causal asymmetry) (Ragin, 2000; Ragin & Fiss, 2008). These theories provide a foundational analytical framework from macro and meso perspectives to integrate and coordinate the broad phenomena surrounding the impact of digitalization on regional income disparities.

This study's findings reveal four distinct, context-specific configurational patterns by which digitalization reduces regional income disparities. In particular, digital inclusion and digital finance emerge as broadly positive contributors across these configurations, while severe digital deficiency consistently leads to worsening inequality. These insights highlight the necessity of considering both digital and contextual factors in tandem. By demonstrating how different digitalization pathways in the form of configurations, under varying economic, governance, and openness conditions, can either alleviate or exacerbate regional inequalities, and present the spatiotemporal characteristics of the configurations. Crucially, we highlight policy-relevant mechanisms that can guide different stakeholders to design digitally enabled strategies for more equitable regional outcomes. This is vital not only for scholars but also for public officials who design development programs, private investors who fund digital ventures, and civil society organizations that advocate for social inclusion. This paper offers actionable insights for governments seeking to align digitalization strategies with inclusive development goals. Furthermore, the findings presented here can inform international development agencies, guiding aid and capacity-building efforts toward digital pathway.

The paper is structured in four main sections. First, it reviews the literature on the impact of digitalization on regional economic disparities and proposes an analytical framework. Second, it describes the research methods, data set, and variable operations used in this study. Third, it presents the main empirical findings. Lastly, it discusses and summarizes the significant research outcomes, emphasizes the policy implications, and suggests directions for further research.

2. Literature review and analytical framework

This paper distils antecedent conditions from existing research and introduces a complex systems perspective along with a configurational approach to the discussion of digitalization and regional income disparities.

2.1. Digital influences on regional disparities

Influencing factors of digitalization can be categorized into three types – digital technology, digital economy, and digital governance – based on their stages of development and application domains, encompassing five key elements. Existing research has provided many insightful conclusions by examining these factors individually.

2.1.1. Digital technology

According to the stage division from R&D to diffusion (Liu & Song, 2023), innovations in digital technology itself, alongside equitable access to technological resources, are widely recognized as fundamentally affecting regional disparities. Neo-Schumpeterianism and the techno-economic paradigm theory underscore that new technology development leads to significant changes in price structures, altering behaviors of various economic agents (Hanusch & Pyka, 2007; Perez, 2010). Recent studies show that diverse forms of innovation can work in tandem with traditional resources to facilitate regional economic development (Toma & Laurens, 2024).

In terms of technological innovation, digital technologies break the spatial distribution pattern of innovative elements through their high penetration, mobility, and synergy, impacting regional economic disparities. This includes catch-up effects, sharing effects, innovation effects, and resource allocation effects (Madsen, 2007; Sorbe et al., 2019; Tranos et al., 2021). Digital technology promotes information flow between regions, offering more opportunities and markets (Löfving et al., 2022; Neogi, 2020; Tchamyou et al., 2019), leading to regional economic homogenization (Breuer et al., 2013; Carey, 2008). For example, the South African government has enhanced financial sector expansion through ICT advancement, consequently diminishing wealth disparities (Tchamyou et al., 2019). However, some scholars also suggest that digital technology and income inequality advance hand-in-hand (Ciffolilli & Muscio, 2018; Georgescu & Kinnunen, 2021). Relatively developed areas have an advantage in attracting high-tech talents, exacerbating regional inequalities (Florida & Mellander, 2016).

In terms of digital inclusion, many studies indicate that the inclusive use of ICT can effectively promote income growth and reduce economic disparities between regions. For example, in Turkey, Internet infrastructure enhancements reduced the timeframe required for regional convergence toward equilibrium conditions and minimized variations between these states (Celbis & de Crombrugghe, 2018). Hollman et al. (2020) found that inadequate internet access and usage significantly limited economic development in these areas, further exacerbating urban-rural income gaps. Since marginalized communities might lack the skills or resources to benefit from new technologies, advancements in digital infrastructure may inadvertently widen the digital divide (Ragnedda & Muschert, 2013). Overall, by enhancing digital inclusion, residents in impoverished areas can access better education and economic opportunities, thereby narrowing regional income disparities (Robinson et al., 2015).

2.1.2. Digital economy

From the digital economic perspective, the focus is primarily on digital industries as the main carriers of economic activity and on digital finance, which serves a supportive and service function (Kling & Lamb, 1999; Moulton, 1999). Neoclassical economic theory highlights that in an ideally competitive market, resources are allocated to individuals and firms that can use them most efficiently, potentially reducing economic disparities through a "trickle-down effect." However, market failures may exacerbate these disparities (Kochevrin, 1988).

In terms of digital industries, some scholars argue that they can facilitate regional element circulation, promote industrial upgrading, improve industrial layouts, enhance inter-regional division of labor and cooperation, and promote economic growth in underdeveloped areas, thereby narrowing regional disparities (Si, 2023; Xu et al., 2023; Zhong et al., 2021). In Brazil,

digital trading platforms have improved trade openness, enabling greater participation from smaller enterprises in international commerce, thereby helping to reduce income inequality (Yin & Choi, 2022). Conversely, other researchers have discovered that digital sector expansion may accelerate productive resource concentration in already developed regions and potentially trigger industrial counter-infiltration patterns, expanding economic developmental gaps between territories (Duan & Shao, 2020; Wang et al., 2022b; Wang et al., 2024), such as e-commerce exacerbating economic imbalances within counties (Lu & Hong, 2023).

In terms of digital finance, it dismantles obstacles present in conventional banking frameworks and enhance accessibility to monetary services, thus narrowing the income and development disparities between regions (Xiong et al., 2022; Ding & Kang, 2024). The Indian government, through innovative digital payment and lending platforms, especially via the Unified Payments Interface (UPI), has reduced financial exclusion and narrowed the income gap (Demir et al., 2022). However, owing to delayed infrastructural development and technological adoption in economically disadvantaged communities, coupled with insufficient digital competence and skepticism toward computerized banking operations, the capacity of fintech to foster inclusivity may be compromised (Siddik & Kabiraj, 2018), thereby widening the development gap between underdeveloped and developed regions (Deng et al., 2023b; X. Liu et al., 2022).

2.1.3. Digital governance

From the perspective of digital governance, governments often play a crucial "meta-governance" role in technology-economic contexts (Sørensen & Torfing, 2009), and their digitalization has received significant attention for its impact on inequalities. The innovation systems framework, as articulated in studies of technological transitions, asserts that novel technological-industrial interplays demand complementary governance frameworks and corresponding community infrastructures (Perez, 2010). In Finland, extensive online governmental services have helped reduce public service disparities between regional communities (Kiviaho & Einolander, 2023). However, studies suggest that the realization of this mechanism may require stringent conditions (Jia & Hua, 2023; Levesque et al., 2024; Ramadani et al., 2022; Ullah et al., 2021). Practices such as e-government have also been found to exacerbate inequalities (Ramadani et al., 2022). Cases from Australia's welfare services' intelligent systems demonstrates that existing punitive service paradigms lead to the replication or reinforcement of exclusion against vulnerable groups (Park & Humphry, 2019).

2.2. Contextual heterogeneity

Context influences the occurrence of agent behaviors and the functional relationships between variables (Johns, 2006). The link between digitalization and regional disparities is considered dependent on other technological, economic, and political forces, as well as stages of development (Bauer, 2018; Liu et al., 2024; Mack et al., 2011; Shiu & Lam, 2008). Toma and Laurens (2024) highlight that regions often differ not only in their ability to adopt innovation but also in their capacity to preserve and leverage traditional forms of knowledge, which underscore the importance of designing context-specific strategies. The competing views and findings regarding the mechanisms of digitalization on regional inequalities have prompted scholarly attention to the impact of contextual heterogeneity.

2.2.1. Economic level

The economic level is a key variable in explaining regional differences within countries, and its complex impact on digitalization is increasingly evident (Barrios & Strobl, 2009; Lessmann, 2014; Petrakos et al., 2005). Some studies have found that more economically developed regions, with the aid of advanced digital technologies and infrastructure, effective digital economy policies, and inclusive digital finance systems, can significantly reduce regional inequalities (Li et al., 2020; Liu & Song, 2023; Raychaudhuri & De, 2010). In contrast, empirical evidence from relatively less developed regions suggests that promoting digital technology innovation and developing digital industries can lead to greater economic growth and effectively promote balanced regional economic development (Galindo-Martín et al., 2019; Liu et al., 2024; Sorbe et al., 2019; Wang et al., 2024).

2.2.2. Governance level

Governance plays a crucial role in mitigating regional disparities (Liu et al., 2024). The governance level is intrinsically connected to the creation and execution of regional advancement strategies, consequently shaping harmonized spatial progress (Ezcurra, 2019). Research indicates that government intervention in the digitalization process has a dual role, both facilitating guidance and regulation of digital development and potentially affecting its efficiency and outcomes (Liu et al., 2021; Song et al., 2020; Wang et al., 2022a). Moreover, despite views that government intervention could negatively impact the narrowing of regional disparities (Li & He, 2022), competent governance can foster parity in regional service provision through the digital economy (Xu et al., 2023).

2.2.3. Degree of openness

Research examining how trade liberalization and cross-border economic flows influence territorial development imbalances has proliferated across economic geography literature, yielding an intricate mosaic of occasionally contradictory empirical evidence (Behrens & Thisse, 2007; Ezcurra, 2019; Krugman & Elizondo, 1996). Baldwin (1989) argues that trade liberalization has both static effects, from resource reallocation, and dynamic effects, from capital accumulation and technology diffusion, leading to long-term improvements in productivity and welfare. Baldwin and Robert-Nicoud (2004) caution that while trade liberalization boosts productivity through static gains, it can slow dynamic growth due to industry shifts, which may exacerbate income inequality over time. Digital pathways, including digital technologies and industries, have been identified as having diffusion effects, backwash effects, and learning effects, capable of both promoting coordinated regional development and triggering new inequalities (Guo et al., 2023; Lu & Hong, 2023; Myrdal, 1957; Williamson, 1965).

2.3. Literature review

Although comprehensive investigations into digitization's influence on regional revenue imbalances exist, findings remain inconsistent and sometimes contradictory (see Table 1). These inconsistencies arise not only from measurement issues, such as the use of different indicators or the neglect of non-linear relationships, but also from variations in theoretical perspectives, methodological approaches, sample selections, and contextual differences (Barrios & Strobl, 2009; Lessmann & Seidel, 2017). For instance, some studies focus on developed econo-

Table 1. Impacts of digitalization and context on regional income disparities

Dimension	Positive	Negative/Ambiguous
Digital innovation	Enhances knowledge spillovers, promotes inclusive growth through technology diffusion and improved resource allocation under suitable conditions	Exacerbates inequalities if unevenly accessed or concentrated in certain regions, reinforcing spatial disparities
Digital inclusion	Reduces digital divide, improves access to education and markets, fosters balanced regional development if infrastructure and skills are in place	Without appropriate digital skills, the development of digital infrastructure may widen regional disparities
Digital industry	Facilitates industrial upgrading, inter-regional trade, and SME participation, potentially narrowing disparities under supportive contexts	May concentrate in developed areas, shifting resources away from lagging regions, potentially widening gaps
Digital finance	Increases financial inclusion, reduces traditional barriers, and can narrow regional income gaps by broadening economic participation	Lack of digital literacy, trust, or stable infrastructure may limit benefits, potentially reinforcing inequalities in underdeveloped regions
Digital governance	Improves public service delivery, supports equalization of public services, fosters transparency and equitable resource distribution	Poorly implemented or punitive digital governance may exacerbate exclusion and inequalities, especially where governance capacity is weak
Economic level	Higher economic development can leverage digital tools more effectively to reduce disparities	Economically backward regions may effectively promote balanced development of regional economies by promoting digital technology and digital economy.
Governance level	Strong governance ensures fair distribution of digital dividends, supports balanced development	Excessive intervention and regulation may hinder the development of digitalization and the spread of its dividends, even if the starting point is good
Degree of openness	Facilitates knowledge spillovers, technology diffusion, and global learning, potentially reducing disparities if gains are well-distributed	Without complementary policies, openness may lead to uneven concentration of benefits in already developed regions, thus widening gaps

mies with advanced digital infrastructures, while others examine developing regions where digitalization is still emerging, leading to divergent conclusions. Additionally, many studies have failed to adequately consider the intricate, nonlinear, and context-specific character of digitalization's impact on regional disparities, often treating digital factors in isolation and overlooking their interactions within specific contexts (Ezcurra, 2019; Liu et al., 2024). These complexities underscore the need for an integrative analytical approach that can accommodate non-linearity and the multifaceted, context-dependent nature of digitalization's impact on regional income disparities.

Acknowledging the complex dimensions of digital phenomena, various researchers caution against an overreliance on singular conceptual frameworks or rudimentary "more is better" linear models, suggesting this approach is inadequate for comprehending digital transition dynamics (Orlikowski & Baroudi, 1991; Park et al., 2020). To this end, various theoretical frameworks have been proposed, including digital ecodynamics (El Sawy et al., 2010), socio-technical systems theory (Trist, 1981), the TOE (Technology, Organization, and Environ-

ment) framework (Tornatzky & Fleischer, 1990). These frameworks aim to provide a more structured analysis of the interplay between digitalization and the economy by considering multiple dimensions and their interactions. Despite the progress made by these frameworks, they remain insufficient to comprehensively explain the relationship between digitalization and regional inequality. The intricate and changing character of technological implementation necessitates employing holistic methodologies capable of capturing the multidimensional interactions and environmental dependencies affecting regional economic disparities.

Taken together, the conflicting evidence and multifaceted complexities indicate that existing approaches have not fully captured the non-linear, context-dependent nature of digitalization's impact on regional income disparities. These considerations underscore the importance of a more integrative and configurational perspective. Therefore, this study seeks to address the following central research question: *How do digital factors*, *under varying contextual conditions*, *combine to influence the reduction or expansion of regional income inequalities?*

2.4. Complex systems perspective and configurational theory: an analytical framework

The complex systems perspective and configurational theory provide the theoretical basis for this study. The complex systems perspective, proposed by Arthur (2018) it assumes that market agents are highly interdependent, and economic activities are undefined. Economic systems are characterized by multiple equilibria, path dependency, unpredictability, and asymmetry (Arthur, 2018), with no single optimal equilibrium existing (Arthur, 2021). Given that complex economic systems have ecological, combinatorial, dynamic, multi-factor interactive, and multi-level interactive characteristics, the complex systems perspective proposes inductive rather than deductive reasoning as an effective way to analyze complex issues, and it suggests the adoption of new methodologies such as combinatorial mathematics (Arthur, 2018). According to this theory, the impacts of various digital factors on regional disparities are not isolated but are influenced by multiple other digital factors and contexts. Different combinations of these factors can produce additional effects, ultimately leading to a variety of causal mechanisms.

Configurational theory provides a more meso-level epistemological and methodological foundation (Fiss et al., 2013). When digital factors and contextual conditions form specific combinations, "configuration effects" emerge. Configurational theory emphasizes that outcomes are determined by combinations of multiple conditions rather than single factors. Similar components can produce divergent results depending on how they interact and combine with surrounding contextual variables (Miller, 1996). The combinatory nature of digitalization results in "multiple configurational causal relationships," where various causes combine in complex and often equivalent ways to produce specific outcomes (Park et al., 2020). This enables understanding the impact of digitalization. Without considering the interactions between individual factors and other factors, a comprehensive understanding is unattainable.

Based on this, we construct an analytical framework, as shown in Figure 1. For analytical purposes in our framework, we conceptualize "configuration effects" as the explanatory pathways emerging when digital and environmental conditions combine, subsequently affecting

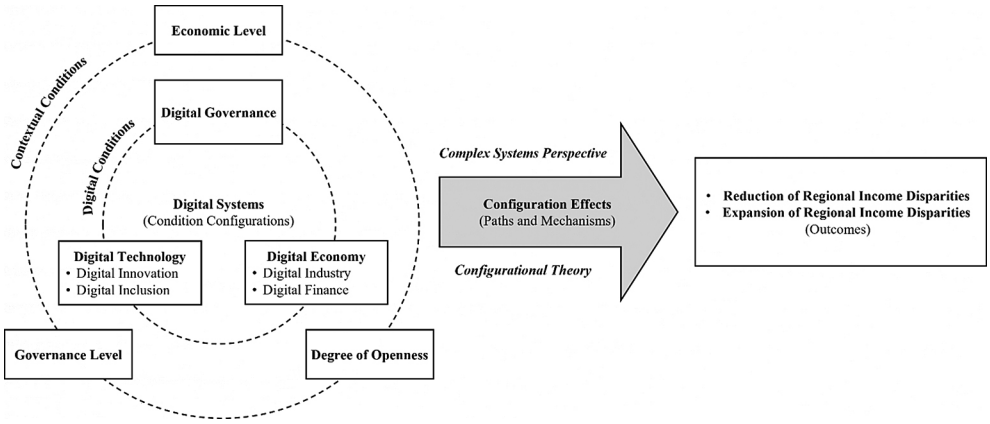


Figure 1. Theoretical analytical framework

regional inequality distributions. The transformation dynamics of digital economic systems demonstrate that socio-economic contexts alongside specific technological enablers typically influence regional income disparities not through isolated mechanisms or linear aggregations, but through multifaceted combinatorial arrangements.

Firstly, the transformation process within the digital domain takes place in diverse and multifaceted environmental settings. Contexts consist of external conditions that can exert key influences, including economic level, governance level, and degree of openness, which provide resources, constraints, incentives, etc., for digital transformation. The combinatorial and variable nature of specific contextual conditions affects the digital mechanisms and may lead to different digital pathways producing similar impacts or different effects of the same digital pathway. As indicated by Toma and Laurens (2024), synergy between new technologies and deeply rooted practices can enhance regional performance when properly configured.

Secondly, various digital elements collaborate to establish multifaceted arrangements, functioning collectively. Through literature review, we identify key digitalization factors, including digital technology (digital innovation, digital inclusion), digital economy (digital industry, digital finance), and digital governance. The digital technology domain focuses on the innovation of digital technologies and the inclusive use of digital technologies. Within technological advancement frameworks, digital industry and digital finance represent core elements emphasized for market development and fiscal advancement. Digital governance addresses the evolution of administrative infrastructure and state-level operational protocols. The impacts of these factors on regional income disparities are neither isolated nor mechanically additive but are determined by configurations, which require specific analysis.

Finally, particular combinations of environmental conditions and digital conditions further integrate to establish multiple equivalent or distinct-effect arrangements, facilitating the diminishment or amplification of regional income disparities. Unlike previous studies that examine these factors individually or assume linear relationships, the configurational analysis based on this framework can capture the inherent complexity and heterogeneity in the digitalization processes of different economies.

3. Research design

3.1. Research methods and research routes

Within the epistemological structures of empirical social inquiry, scholars emphasize the importance of differentiating between some fundamental variable association patterns (Dul et al., 2020). Conventional regression-based methods primarily focus on average effects, assuming linearity and additive separability among factors. Such methodologies prove inadequate for investigating the multifaceted, non-linear, and environmentally contingent characteristics of digitalization's impact on regional disparities. QCA conceptualizes analytical cases as combinatorial arrangements of explanatory factors, facilitating the evaluation of intricate causal patterns including concurrent influencing elements, reverse causation logic, and multiple solution pathways, rendering it appropriate for analyzing the sophisticated conditional requirements and sufficient arrangements between contextual factors, digital pathways, and regional income disparities (Ragin, 2000). Panel fsQCA is a newer and improved method (Castro & Ariño, 2016). By integrating panel data, Panel fsQCA incorporates the time and space dimensions, allowing us to observe how configurations evolve over time and across regions. It goes beyond static cross-sectional analyses, offering a richer portrayal of how digital and contextual factors dynamically combine to influence regional inequalities.

However, while fsQCA identifies combinations of conditions that are sufficient for an outcome, it does not explicitly quantify whether certain conditions are indispensable prerequisites. Necessary Condition Analysis (NCA) fills this gap by determining the presence and effect size of necessary conditions (Dul et al., 2020). This complementary perspective provides insight into which conditions must be present, though not necessarily sufficient, for the reduction or expansion of regional disparities. Thus, NCA adds a valuable layer of nuance, ensuring that we do not overlook key foundational elements required to achieve more equitable outcomes.

Together, the combination of Panel fsQCA and NCA offers a powerful toolkit for unraveling the complexity of digitalization's regional effects. Similar methodologies have been successfully applied in related domains to untangle complex causal relationships where multiple interdependent factors shape outcomes. For instance, Vasist and Krishnan (2024) applied fsQCA and NCA to examined how various aspects of national artificial intelligence capabilities contribute to sustainability objectives, while Ding (2022) employed these methods to assess the complex determinants of innovation outcomes across different countries. Drawing on these methodological precedents, our study employs Panel fsQCA and NCA to identify crucial digital configurations, illuminate their temporal patterns, and reveal necessary conditions, thus providing a more comprehensive and methodologically robust account of how digital transformation affects regional income inequality.

The empirical analysis approach of this study is as follows: First, using NCA and the necessity analysis within Panel fsQCA, we examine whether the reduction (or expansion) of regional income disparities requires any single condition, and assess the degree of necessity of individual conditions, thereby justifying the necessity of configurational analysis and complementing its findings. Second, through the sufficiency analysis of Panel fsQCA, we identify several equivalent condition arrangements associated with decreased (or heightened) region-

al income disparities and investigate the combinatorial characteristics of condition variables within each configuration to extract typical patterns of causal mechanisms. On this basis, we analyze the between-group consistency and within-group consistency of configurations. Then, we conduct robustness tests on the main empirical findings.

3.2. Sample selection

To conduct set-theoretic panel analysis, a symmetrically structured dataset is essential for maintaining analytical coherence and temporal comparability. For our assessment of how digital factors' configurations affect regional economic disparities, we developed a uniformly structured longitudinal dataset covering 134 economies worldwide over the 2012–2021 period. The sample selection process adhered to the following criteria: (1) Data availability and completeness; (2) Data quality and reliability; (3) Balanced panel requirements. Based on these criteria, we used all global economies as the initial sample frame, collected data from mainstream and authoritative data sources, and removed samples with missing data, resulting in 134 economies from 2012 to 2021. The sample set encompasses different contextual and digitalization states, balancing data availability and diversity, enabling thorough examination of digitalization's varied impacts across different settings. Supplementary material A provides detailed information on the economies included in the sample, including their codes, regions, and income levels.

3.3. Definition and operationalization of variables

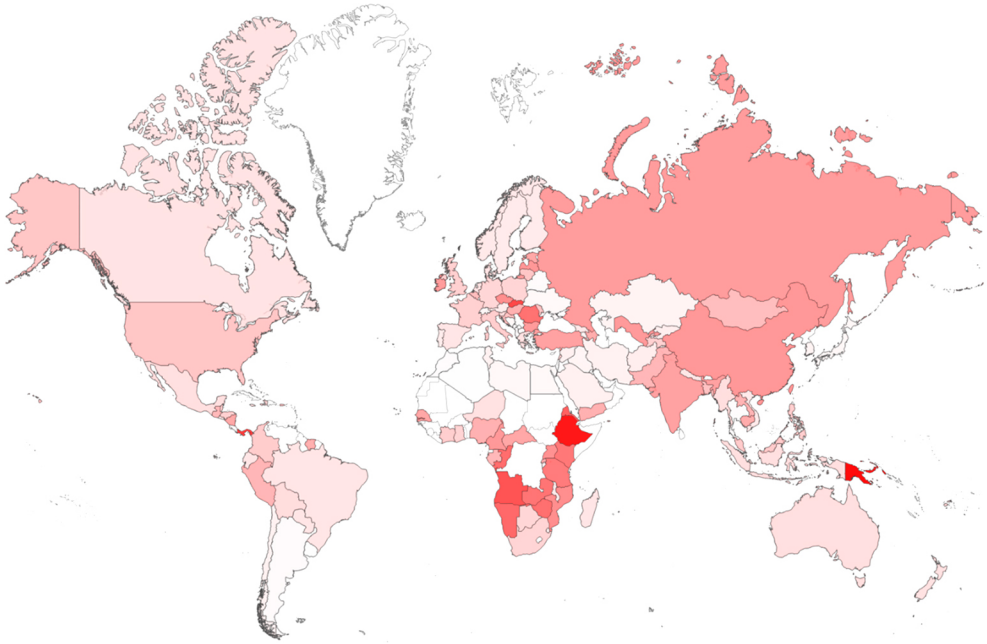
3.3.1. Regional income disparities

Our research quantifies regional economic disparities by utilizing the gross domestic product per person at the subnational level, converted to USD thousands with purchasing power adjustments (2011 baseline), obtained from the Area Database of the Global Data Lab (Smits & Permanyer, 2019). This dataset represents the most comprehensive measure of subnational income to date, with the broadest time span and sample size and scientific method of dealing with missing values. For high-income and some middle-income economies, subnational data are based on data provided by national statistical offices and Eurostat. For most low- and middle-income economies, the data are derived through regression predictions and calibration against the International Wealth Index (IWI) from the Area Database of the Global Data Lab (Smits & Permanyer, 2019).

Various quantitative techniques, including the Gini coefficient, Theil index, and coefficient of variation, have been extensively employed to evaluate geographical economic imbalances (Ezcurra, 2019; Lessmann & Seidel, 2017; Liu et al., 2024).

The differences in population-weighted and unweighted subnational inequality indices across countries are minimal (Lessmann & Seidel, 2017). Moreover, due to substantial missing data on subnational populations, choosing to use population weighting would mean a drastic reduction in sample size. Therefore, this paper uses the unweighted Theil index to measure regional inequality. The Theil index, based on information-theoretic entropy principles, provides a mathematically precise representation of regional developmental disparities. It satisfies the transfer principle (Pigou-Dalton principle) and is more sensitive to changes in

medium-income levels, better reflecting gradual changes in regional development. Of course, the Theil index's drawback is that its calculation is relatively complex, and its numerical range is not fixed, posing challenges to the robustness of its measurement. In light of this, we use other inequality measures (Gini coefficient and coefficient of variation) for robustness checks. The Theil index of intra-national regional income disparities among sample economies is shown in the Figure 2 below.



Note: White areas represent missing samples, and shades of red indicate increasing levels of internal regional income disparities.

Figure 2. Regional income disparities (2012–2021 average, Theil Index)

3.3.2. Digital innovation

In this study, digital innovation is measured using the entropy weighting method applied to indicators such as scientific and technical journal articles per capita, the percentage of high-technology exports (as a proportion of manufactured exports), and the value-added of high-technology manufacturing (as a percentage of manufacturing value-added) (Shahbaz et al., 2022; Xiang et al., 2022). These indicators collectively capture the creation, commercialization, and economic impact of digital innovations, encompassing the major stages of the digital technology innovation chain. Data are sourced from the World Development Indicators (World Bank, 2024).

3.3.3. Digital inclusion

Following methodological discussions (Alhassan & Adam, 2021; Sharp, 2024), we measure digital inclusion based on the methodology of the Information and Communication Technology Development Index (IDI) developed by the International Telecommunication Union (ITU,

2023). The IDI consists of three main dimensions: ICT infrastructure (40%), ICT usage (40%), and ICT skills (20%). ICT infrastructure includes fixed telephone lines per 100 inhabitants, mobile cellular subscriptions per 100 inhabitants, international internet bandwidth (bits/s), percentage of households with a computer, and percentage of households with internet access. ICT usage includes the percentage of individuals using the internet, fixed broadband internet subscriptions per 100 inhabitants, and active mobile broadband subscriptions per 100 inhabitants. Finally, ICT skills are measured by adult literacy rate, gross enrollment ratio in secondary education, and gross enrollment ratio in tertiary education. These composite indicators comprehensively reflect the development level of information technology in terms of infrastructure, usage, and skills, helping to assess the digital inclusion of each country. Data are derived from the World Development Indicators (World Bank, 2024) and the International Telecommunication Union (2023).

3.3.4. Digital industry

We measure the development level of the digital industry using the entropy weighting method for metrics such as ICT service exports (current USD), ICT service exports (as a percentage of service exports), ICT goods exports (as a percentage of total goods exports), and ICT goods imports (as a percentage of total goods imports) (Dong et al., 2022; Sahay et al., 2020; Shahbaz et al., 2022). These indicators reflect the scale and market performance of the digital industry in international trade. Data are sourced from the World Development Indicators (World Bank, 2024).

3.3.5. Digital finance

Drawing on existing research, our digital finance assessment utilizes information-theoretical weighting techniques to process several metrics, including ATM accessibility rates (calculated per 100,000 population), account ownership at a financial institution or with a mobile-money-service provider (% ages 15+), making or receiving digital payments in the past year (% ages 15+), and borrowing from a financial institution or using a credit card (% ages 15+) (Ozturk & Ullah, 2022; Shen et al., 2020; Tchamyou et al., 2019; Tchamyou & Asongu, 2017). These indicators collectively capture the accessibility, penetration, activity, and level of digital financial inclusion within economies, thereby illustrating the extent to which digital finance contributes to narrowing regional income disparities through inclusive economic participation. Data are obtained from the World Development Indicators (World Bank, 2024) and the Global Financial Inclusion database (Demirgüç-Kunt et al., 2020).

3.3.6. Digital governance

We utilize data from the United Nations E-Government Development Index (EGDI), focusing on the Online Service Index (OSI) and E-Participation Index (EPI), to measure the development of digital governance (Shahbaz et al., 2022; Zou et al., 2023). These indexes reflect the capabilities of digital governance services and the outcomes of digital collaborative governance. Therefore, this paper takes their average value. These indices not only assess the capabilities of digital governance services and the outcomes of digital collaborative governance but also measure the degree of digital inclusion in governance by evaluating the accessibility and participation of these services for citizens (United Nations, 2024).

3.3.7. Economic level

We use per capita GDP as a proxy variable for economic level, following common practice (Ezcurra, 2019; Hawash & Lang, 2020). It provides a comprehensive measure of a country's economic status. The data is derived from the World Development Indicators (World Bank, 2024).

3.3.8. Governance capacity

We adopt the World Bank's Worldwide Governance Indicators (WGI) to represent the level of government governance (Ezcurra, 2019; Shahbaz et al., 2022). The WGI covers key governance dimensions such as voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption.

3.3.9. Degree of openness

We use the KOF Index of Economic Globalization (de facto component) to measure the degree of openness, offering a broader perspective that includes trade and financial globalization (Dreher, 2006; Ezcurra & Rodríguez-Pose, 2013). This paper focuses on the factual dimension and takes the average of secondary indicators.

For a comparison of alternative approaches to measuring the variables, see Supplementary material B.

3.4. Data pre-processing and analysis procedure

For initial data treatment, our approach involved applying exponential curve interpolation methods alongside group-specific average substitution techniques (categorized by economic development tier and geographical zone). Secondly, to account for temporal dynamics in how digital factors influence regional disparities and to mitigate endogeneity concerns, in line with common practice (Jia & Hua, 2023; Wang et al., 2024), this paper applied a one-period lag to the condition variables.

In the data calibration for QCA, we used the direct method based on variable characteristics, setting the 95th percentile, 50th percentile, and 5th percentile as calibration anchors, representing full membership, crossover point, and full non-membership, respectively. For easier understanding, we reverse-calibrated the regional income disparities variable, meaning that higher final values indicate smaller disparities.

In the analysis, we started with necessity analysis, establishing 0.8 as the minimum parametric criterion for determining which factors constitute prerequisites for regional disparity outcomes. Subsequently, following empirical practices (Greckhamer et al., 2013), we utilized Boolean minimization procedures based on the constructed truth matrix, applying a consistency threshold of 0.8, proportional reduction in inconsistency parameter of 0.75, and requiring configurations to have a minimum observational frequency of 6 cases. The calibration settings for membership are shown in Table 2.

Table 2. Variable measurement and calibration results

Conditions	Data Source	Full membership	Cross-over point	Full non-membership
Regional income disparities	International Wealth Index (IWI)	0.001094	0.029092	0.134234
Digital innovation	World Development Indicators	0.154442	0.04777	0.008948
Digital inclusion	World Development Indicators; International Telecommunication Union (ITU)	0.634694	0.304876	0.09635
Digital industry	World Development Indicators	0.055381	0.008033	0.001353
Digital finance	World Development Indicators; Global Financial Inclusion Database	0.582541	0.217141	0.034058
Digital governance	UN E-Government Development Index (EGDI)	0.941304	0.488139	0.101845
Economic level	World Development Indicators	48465.79	5425.897	584.0938
Governance level	World Governance Index (WGI)	1.637271	–0.22374	–1.39002
Degree of openness	KOF Index of Economic Globalization	82.71381	59.35983	30.17806

4. Results analysis

4.1. Necessity analysis and NCA: what are the necessary conditions for a single condition?

We first conducted a necessity analysis. The purpose of QCA's necessity analysis is to check whether individual condition variables are necessary conditions for the occurrence of the outcome variable. In Panel fsQCA analysis, if the pooled consistency is greater than 0.9 and the pooled coverage is greater than 0.5, a condition is generally considered necessary. As shown in Table 3, although many condition variables have a pooled coverage greater than 0.5, the more critical pooled consistency values are all less than 0.9. The results fail to provide compelling evidence for any condition's necessity status.

Therefore, we supplemented our analytical approach with Necessary Condition Analysis to deliver more nuanced insights into prerequisite relationships. NCA determines prerequisite conditions through examination of necessity magnitude and statistical significance of causal factors (Dul et al., 2020). The effect size value approaching 1 indicates a larger effect (Dul et al., 2020). NCA provides ceiling regression (CR) for continuous variable analysis. Supplementary material C presents the complete necessity analysis outcomes for each condition, with effect sizes and P-values calculated through the CR approach. Conditions qualify as necessary for the outcome condition when they satisfy two criteria simultaneously: the calculated effect magnitude must surpass the 0.1 threshold and statistical tests must confirm significance. (Dul et al., 2020). The results show that no condition variables simultaneously meet the threshold requirements for effect size and P-value, indicating that no conditions constitute necessary conditions for the reduction or expansion of regional income disparities.

Table 3. Results of the QCA necessity analysis

	Reduction of regional income disparities		Expansion of regional income disparities	
	Pooled consistency	Pooled coverage	Pooled consistency	Pooled coverage
Digital innovation	0.616	0.695	0.595	0.576
~Digital innovation	0.624	0.643	0.684	0.604
Digital inclusion	0.666	0.737	0.553	0.525
~Digital inclusion	0.57	0.598	0.722	0.65
Digital industry	0.596	0.724	0.562	0.586
~Digital industry	0.659	0.637	0.735	0.609
Digital finance	0.643	0.719	0.576	0.552
~Digital finance	0.599	0.622	0.707	0.629
Digital governance	0.65	0.704	0.597	0.555
~Digital governance	0.589	0.63	0.682	0.625
Economic level	0.604	0.748	0.523	0.556
~Economic level	0.642	0.611	0.763	0.623
Governance level	0.666	0.721	0.611	0.567
~Governance level	0.6	0.643	0.7	0.642
Degree of openness	0.66	0.702	0.616	0.562
~Degree of openness	0.588	0.641	0.673	0.629

Furthermore, we analyzed the necessity analysis results of each year's cross-section (see Figures 3–4, and Supplementary material D). In the aspect of reducing regional income disparities, digital industry, digital finance, digital governance, and degree of openness have shown a significant positive impact since 2016–2017. This reflects a trend of strengthening the role of digitalization in reducing regional income disparities. Additionally, no widespread necessary conditions for digitalization that could lead to an increase in regional income disparities were found.

4.2. Sufficiency analysis: what configurations affect regional income disparities?

Through truth table construction and Boolean minimization procedures, we discerned distinctive configurational patterns. Given the substantial variational heterogeneity in country-level resources and contradictory empirical evidence in scholarly literature, we avoided imposing preconceived directional assumptions regarding how antecedent factors might influence outcomes. The analysis yielded three categories of QCA outputs: enhanced simple solutions, intermediate solutions, and complex solutions. Our analytical approach prioritizes examination of the intermediate solutions while drawing on parsimonious solutions as complementary evidence for distinguishing between core and peripheral causal factors in the configurational patterns.

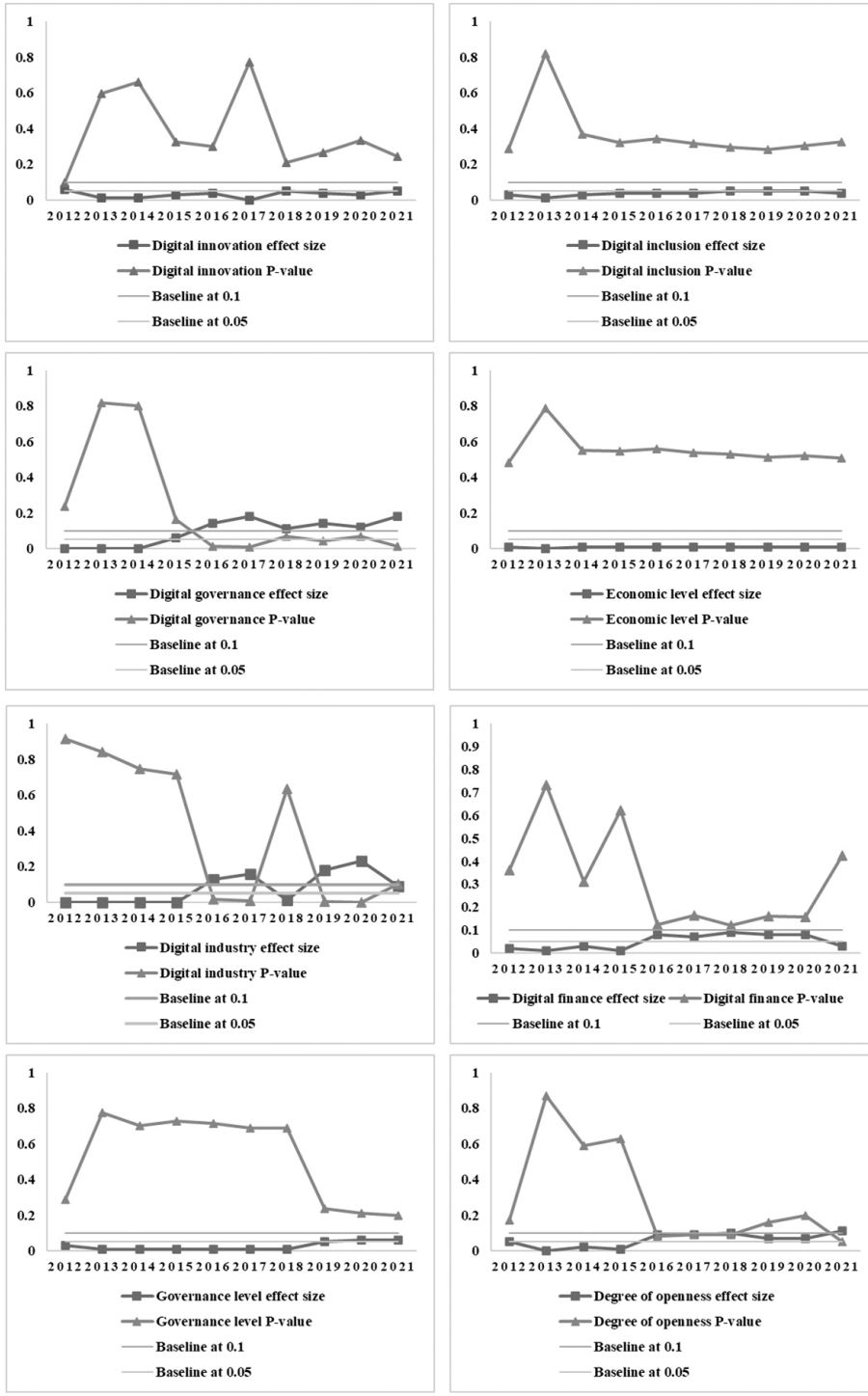


Figure 3. Annual results of NCA (reduction in regional income disparities)

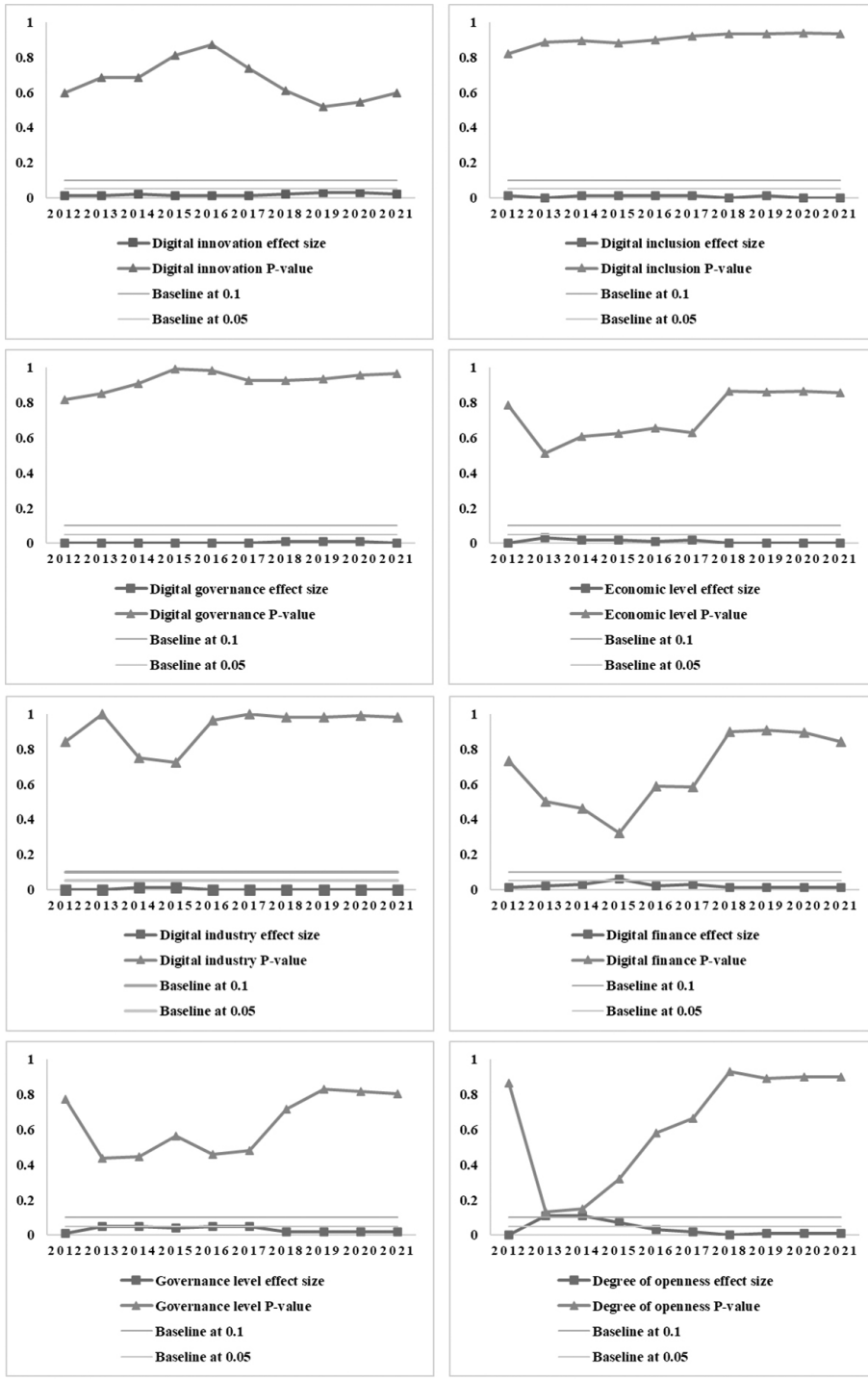


Figure 4. Annual results of NCA (increase in regional income disparities)

Each configuration represents a specific combination of digitalization factors and contextual conditions. The presence or absence of conditions in configurations is indicated using specific symbols: (1) ●: presence of a core condition; (2) ⊗: absence of a core condition; (3) □: presence of a peripheral condition; (4) ⊠: absence of a peripheral condition. Core conditions represent essential causal factors characterized by their presence across both intermediate solutions and parsimonious solutions analyses. Peripheral conditions – identifiable by their exclusive appearance in intermediate solutions but absence from parsimonious solutions – typically exert more modest causal influence. Consistency, quantifies the extent to which cases sharing particular conditions arrangements consistently demonstrate the outcome. Coverage measures the empirical relevance of a causal configuration by assessing what proportion of instances exhibiting the outcome can be explained by the given condition or combination of conditions. PRI, short for "Proportional Reduction in Inconsistency," assists in determining whether a condition is a sufficient condition for the outcome. Elevated PRI values signify greater causal coherence, indicating minimal contradictory evidence within the identified relationship between conditions and outcomes.

As Table 4 shows, there are five configurations that facilitate the reduction of regional income disparities. Each configuration has a consistency value above 0.9 and also exhibits a high PRI. Most have original coverage rates between 0.2 and 0.3. The overall consistency and overall coverage of the solution are 0.907 and 0.405, respectively, indicating good explanatory power. Based on the two dimensions of context and digitalization, by comparing and integrating the configurations, we can distill four models of digitalization promoting the reduction of regional income disparities. The case membership details for each configuration are provided in Supplementary material G.

Table 4. Configurations of regional income disparities

		Reduction of regional income disparities					Expansion of regional income disparities			
		H1	H2	H3a	H3b	H4	NH1	NH2	NH3	NH4
Digitalization	Digital innovation		⊗	●	●	●		⊗	⊠	●
	Digital inclusion	●	●	●	●	●	⊗	⊠	⊠	⊠
	Digital industry	●		□		□	⊗	●	⊗	
	Digital finance	□	□	□	□	⊠	⊠	⊠	⊗	⊠
	Digital governance	□		□	□	⊠	●	⊗	⊗	⊗
Context	Economic level	□	●		□	□	⊠	⊗	⊠	⊠
	Governance level	●	□	⊗	⊗	⊗	⊗	⊗	●	⊠
	Degree of openness	⊗	□	●	●	●	⊠		⊠	⊗
Consistency		0.93	0.926	0.942	0.942	0.945	0.815	0.797	0.821	0.825
PRI		0.769	0.803	0.794	0.813	0.763	0.456	0.484	0.446	0.501
Raw coverage (covS)		0.235	0.298	0.206	0.228	0.175	0.287	0.32	0.273	0.275
Unique coverage (covU)		0.049	0.077	0.011	0.01	0.009	0.037	0.079	0.025	0.023
Overall solution consistency		0.907					0.776			
Overall PRI		0.783					0.527			
Overall solution coverage		0.405					0.467			

First, *comprehensive digital transformation model based on economic prosperity and good governance* (*H1*). Under this configuration, economies with high economic levels (□) and governance levels (●) but limited openness (⊗) can reduce regional income disparities through digital inclusion (●), digital industry (●), digital finance (□), and digital governance (□). Representative economies include Ireland, Argentina, and Jordan. Although these economies are not highly open and have limited high-tech development, other conditions are relatively favorable. This indicates that, supported by strong economic and governance backgrounds, an overall approach to digital transformation can effectively address regional disparities. This configuration reflects that although technological advantages and openness are important (Breuer et al., 2014; Carey, 2008; Nguyen, 2023), promoting the inclusive use of digital technologies based on sound market economies and public governance (Celbis & de Crombrugghe, 2018), and jointly developing the digital economy and digital governance, can also help narrow regional income disparities.

Second, *digital inclusion development model based on a solid overall foundation* (*H2*). Under this configuration, economies with high economic levels (●), governance levels (□), and openness (□) can reduce regional income disparities through digital inclusion (●) and digital finance (□). This pathway indicates that the model has relatively high raw coverage and unique coverage and has broad explanatory power among economies with good foundations in various aspects. Representative economies are Canada, Poland, and Madagascar. The logic of this model lies in that, supported by economic prosperity, good governance, and openness, economies can introduce and learn from external digital technological achievements rather than independent innovation, promote the inclusive use of digital facilities, and develop digital inclusive finance, enabling backward regions to gain latecomer advantages and achieve "leapfrog" economic development. Particularly, investing in the inclusive construction of digital facilities and financial digitalization is important (Robinson et al., 2015). Meanwhile, this highlights the positive effects of participating in the international open system and leveraging external technological achievements (Jadhav, 2022; Myrdal, 1957; Williamson, 1965), but also faces challenges of high external environment requirements and strong dependencies. Additionally, this requires certain economic levels and public governance capabilities, emphasizing that economic strength provides a material basis for digital transformation (Barrios & Strobl, 2009; Lessmann, 2014).

Third, *comprehensive digitalization model based on openness* (*H3*). Under this configuration, economies with high openness (●) but limited governance capabilities (⊗) can reduce regional income disparities through relatively comprehensive digitalization.

This indicates that despite administrative governance constraints, strategically advancing technological innovation initiatives, fostering digital accessibility, and strengthening both digital market structures and e-governance frameworks may successfully diminish geographical economic inequalities. Under this model, the raw coverage of configurations H3a and H3b (0.011, 0.010) is relatively low. From the characteristics of the cases belonging to these configurations, these economies are mostly coastal, with significant disparities between coastal and inland regions, and relatively limited land area or population size. Representative countries include Bosnia and Herzegovina, Panama, and Saudi Arabia. This model demands certain endogenous requirements for digital transformation and is also highly sensitive to external environments. Compared to the H2 and H4 models, this model emphasizes not just the

simple introduction of digital achievements but stresses comprehensive digitalization (Li & He, 2022). Notably, compared to other digital factors, the importance of the digital industry is relatively weak under this model.

Fourth, *digital innovation and inclusion model based on openness and economic foundation* (*H4*). Under this configuration, economies with high openness (●) and certain economic foundations (□) but limited governance capabilities (⊗) can reduce regional income disparities through digital technological innovation and inclusive use, supplemented by the development of the digital industry. This configuration highlights the importance of digital technology for open economies. Representative countries include Kazakhstan and Kenya. Compared to the other three models, the most distinctive feature of the H4 model is its greater focus on the development of "hard power" areas such as digital technological innovation, digital application popularization, and digital industry cultivation (Kong et al., 2023; Si, 2023). The H4 model advocates for blending international connectivity with indigenous technological growth through targeted digital initiatives, providing valuable insights for emerging markets in nascent digitalization phases seeking to address spatial economic imbalances.

To test causal asymmetry, we analyzed the digital pathways and contexts that lead to widening regional income disparities. In the sufficiency analysis, the PRI threshold for forming stable configuration results was set at 0.4, lower than the commonly used 0.7 threshold in academia. The consistency and coverage performances are overall normal. Four configurations represent four models. First, the non-digitalization and digital divide of industry and finance under a comprehensive backward background (NH1; Slovenia, Montenegro, Syria, etc.). Second, non-digitalization of technology, finance, governance, and the digital divide under an economically backward and poorly governed background (NH2; Myanmar, Mauritius, Maldives, etc.). Third, comprehensive non-digitalization under an economically backward and low openness background (NH3; Pakistan, Macedonia, etc.). Fourth, non-digitalization of finance and governance and the digital divide under a comprehensive backward background (NH4; Barbados, Guatemala, Honduras, etc.). Most of the cases are concentrated in less developed economies.

Combined with the affirmative analysis (configurations that reduce regional income disparities), the negative analysis overall supports a viewpoint: digital transformation does not necessarily mean that regional disparities will narrow, but in backward contexts, the lack of digitalization often means the expansion of regional disparities (Bandyopadhyay & Sattarzadeh, 2010; Celbis & de Crombrugghe, 2018). Meanwhile, in the four configurations, individual positive digitalization transformation conditions exist, such as digital innovation (NH4), digital industry (NH2), digital governance (NH1), which to some extent echoes the literature holding cautious views on the role of specific digitalization (Florida & Mellander, 2016; Ramadani et al., 2022). It is noteworthy that the lack of digital inclusion exists in all configurations, inversely supporting its positive role.

4.3. Between consistency analysis: phasic changes in configurational explanatory power

The between consistency in panel fsQCA reveals how effectively configurations account for outcomes across sequential time periods (Castro & Ariño, 2016). Observing the changes in

between consistency of configurations (Figure 5, see Supplementary material E for details), we can see that at the level of reducing regional income disparities, the between consistency of each configuration remains above 0.9, indicating good explanatory power for the outcome. Among these, configurations H1, H3 show a certain degree of declining trend in between consistency, while H4 shows an increasing trend. At the level of expanding regional income disparities, the between consistency of configurations is between 0.75 and 0.85. Except for NH1, the between consistency of configurations shows an overall increasing trend. This means that in the digital era, the lack of digital transformation will increasingly lead to the expansion of regional income disparities within economies. A noteworthy phenomenon is that the explanatory power of H1 and H4 increased slightly in 2020, while the explanatory power of NH1 and NH4 changed from rising to falling in 2020. An important global event during this period is the COVID-19 pandemic. This temporal coincidence suggests the health emergency potentially exerted nuanced yet considerable influence on how digital transformation affected intra-national economic imbalances.

4.4. Within consistency analysis: regional distribution of configurational explanatory power

Within consistency reflects how effectively individual configurations explain outcomes across various economy samples (see Figure 6, Supplementary material F). When examining solution patterns that mitigate subnational economic differences, the assessment of within consistency demonstrates that every combinatorial pattern has good explanatory power for the vast majority of samples, while a few samples show limited explanatory power of solution combinations (Figure 6). It is noteworthy that some configurations show limited explanatory power in economies such as the United States, China, Russia, and Turkey. The characteristics of these economies are that the performance of digital development indicators at the per capita level or as a proportion differs greatly from the absolute scale level. The subnational jurisdictions within these countries approach the overall scale of general economies. On the other hand, in the configurations for expanding regional income disparities, the number of samples with limited explanatory power of configurations is relatively large, and they are mostly concentrated in developing economies, indicating that besides digitalization and contextual factors, there are more factors leading to the expansion of regional income disparities in these economies. Moreover, the within consistency performance of different configurations is similar.

4.5. Robustness tests

Despite QCA gaining popularity as a methodology for examining causal complexity, the robustness of QCA results has been questioned (Lucas & Szatrowski, 2014). To address potential concerns about validity, we implemented several supplementary verification procedures to evaluate the stability of our primary findings regarding configurations that mitigate subnational economic differences.

First, based on various inequality indices obtained during variable measurement, we used the Theil index and coefficient of variation, which are often used besides the Gini coefficient, to construct proxy variables for regional disparities (see Supplementary material H for details). Except for H4, other configurations are consistent or similar.

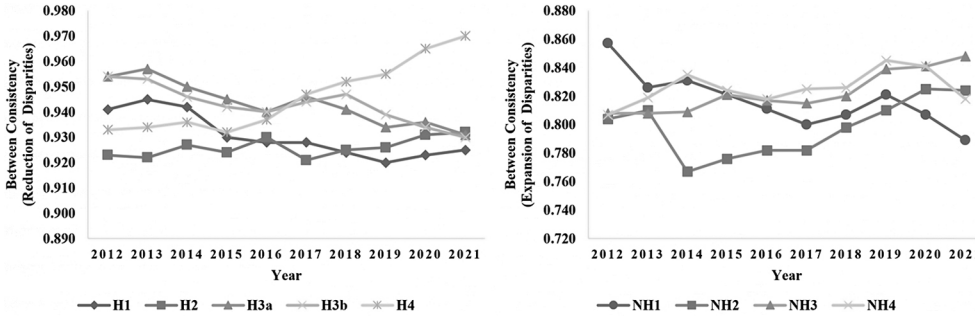
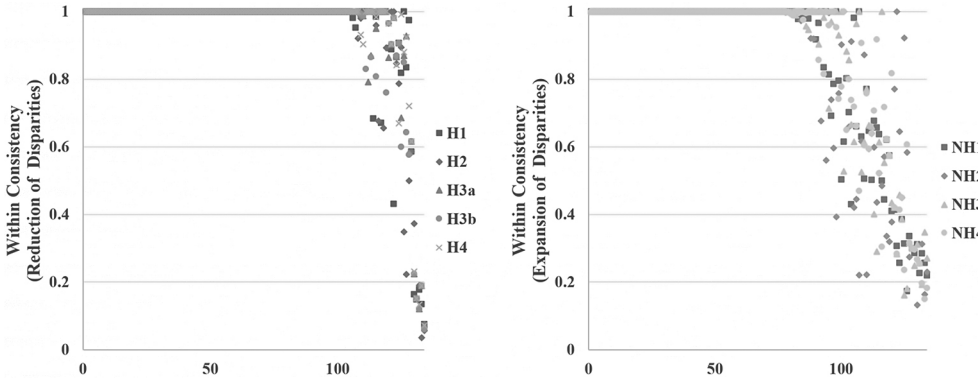


Figure 5. Between consistency analysis



Note: The vertical axis represents within consistency, and the horizontal axis represents samples

Figure 6. Within consistency analysis

Second, we adjusted the key thresholds in QCA (see Supplementary material I). (1) We changed the case frequency threshold for sufficiency analysis to 8 cases, and the new configurations mainly reflected H1, H2, H3 in Table 4. (2) We raise the consistency criterion to 0.85 demonstrated alignment with the primary analytical configurations, indicating robust methodological validity. (3) We attempted to re-analyze the sufficiency analysis without lagging the condition variables (see Supplementary material J). Except for H4, other configurations are consistent or similar.

Collectively, these validation exercises substantiate that our findings exhibit considerable resilience across methodological variations, thereby strengthening confidence in the analytical conclusions presented above.

6. Discussion

This study set out to investigate how digitalization, under various contexts, influences regional income inequality in 134 economies. Employing both Panel fsQCA and NCA, we identified multiple configurational pathways that either alleviate or exacerbate regional disparities. In this Section, we discuss the implications of these findings in more depth.

Firstly, addressing our research question – how digital and contextual conditions jointly shape regional income disparities – our analysis reveals varying impacts across different dig-

italization dimensions and contextual settings. Our necessity assessments through both NCA and QCA methodologies demonstrate that individual variables rarely function as necessary prerequisites for altering regional economic disparity. Meanwhile, since 2016, the necessity of digital industry, digital finance, digital governance, governance level, and degree of openness has increased significantly. Although single variables have limited necessity, when they appear in configurations, the importance of certain digitalization pathways or contexts on regional disparities is highlighted. Under various contextual conditions, digital inclusion is a key component of configurations that reduce regional income disparities. This reinforces the idea that promoting digital inclusion is crucial, regardless of an economy's openness, economic development level, or governance quality (Hargittai & Hsieh, 2013). Additionally, digital finance plays a relatively persistent positive role, emphasizing the value of financial inclusion and broad economic participation in the digital context (Álvarez-Gamboa et al., 2021; Kebede et al., 2023). In terms of context, economic level and openness play broad positive roles, thereby directly informing our central inquiry into which contextual landscapes enable certain digital pathways to effectively reduce regional income disparities. This reflects that regional income disparities are largely a byproduct of regional economic disparities (Barrios & Strobl, 2009; Lessmann, 2014), and supporting the assumption of the importance of external connections in the digital impact mechanism.

More importantly, this paper finds that digital factors have complex configurational effects on regional income disparities under contextual influences, responding to calls and speculations about the complex effects of digitalization (Bauer, 2018; Siregar, 2020; Tchamyou et al., 2019; Venables, 2001). The achievement of narrowing regional disparities is driven by different digital factors and specific contexts through configurations (Arthur, 2018). Specifically, answering the question of which digital-context combinations yield equitable outcomes, we identify four distinct mechanisms emerging from the interplay of contextual conditions and digital factors, including: (1) an integrated digital transformation approach grounded in economic development and effective governance; (2) a digital inclusion development model based on a solid overall foundation; (3) a comprehensive digitalization model based on openness; (4) a digital innovation and inclusion model based on openness and economic foundation. These reveal good digitalization schemes conducive to regional income coordination under different contexts. The negative analysis also demonstrates several mechanisms that play a role in expanding regional income disparities (NH1, NH2, NH3, NH4). Moreover, in those configurations associated with widening disparities, digitalization factors appear as 'absent' or insufficiently integrated, reinforcing our question's focus on understanding how missing or weak digital elements in certain contexts fail to alleviate and may even intensify inequalities. This supports the literature advocating the positive roles of digitalization (Bandyopadhyay & Sattarzadeh, 2010; Celbis & de Crombrugghe, 2018) from the reverse.

The identified configurations exemplify the collaborative mechanisms through which digital elements work together to impact regional income disparities. The emerging substitution effects help integrate contradictory findings based on different economies. For example, in contexts of economic prosperity and openness, "digital innovation + digital inclusion + digital finance + digital governance" and "digital innovation + digital inclusion + digital industry" can substitute each other (H3b, H4); when promoting comprehensive digital transformation,

different contextual conditions can substitute each other (H1, H3a, H3b). On the other hand, the study finds some causal mechanisms that have received little attention, such as the configurational effects of specific digital factor combinations in particular contexts reflected in H4. This provides ideas and evidence for understanding the specific manifestations of decentralized digital causal mechanisms and their differences and commonalities, offering possible directions for more in-depth research.

Building further on the central research question, this paper also captures the dynamic trends and spatial distribution characteristics of digital factors and configurational explanatory power, refining our grasp of which conditions consistently support or hinder the narrowing of regional disparities. From the time dimension, NCA finds that the necessity of digital industry, digital finance, and digital governance has increased since 2016, reflecting the trend of expanding digitalization's impact. Panel fsQCA finds that the role of relatively comprehensive digital transformation pathways (H1, H3) in reducing regional income disparities is decreasing overall, while the explanatory power of digital pathways with focus (H4) is increasing. From the spatial dimension, the case membership distribution of each configuration refines the specific geographical distribution of successful models within economies. Additionally, we capture some changes in the configurational effects of digitalization starting from 2020 (H1, H4, NH1, NH4). This may reflect the impact of the COVID-19 pandemic on macroeconomic and microeconomic aspects within economies, especially accelerating digital transformation and enhancing the specific impact of digitalization on regional disparities. Future research could delve deeper into how major shocks like public health crises modulate the delicate balance of digital conditions and contexts, thereby influencing whether regional inequalities are mitigated or aggravated.

7. Conclusions

Addressing regional economic disparities remains a persistent concern for public institutions and researchers. Digital transformation offers opportunities to reduce regional income disparities, and a plethora of research has emerged around the mechanisms of their impact. However, the widespread findings of competitiveness and ambiguity reflect the need for an integrated analysis of the problem. Our research, leveraging complex systems thinking and configurational theoretical frameworks, examines how various digital elements interact with environmental contexts to influence regional economic disparities across 134 nations during 2012–2021, and employing Panel fsQCA and NCA.

The findings of this paper have policy implications for stakeholders such as national and local governments, policymakers, and international organizations seeking to reduce regional income disparities through digital transformation. First, the positive impact of digital transformation as a whole rather than negative impacts is empirically demonstrated, encouraging economies to carry out more digital transformation practices. Second, the prominent positive role of digital inclusion reflects that it is not merely a byproduct of digitalization but a key part that must be deliberately cultivated. By incorporating digital inclusion strategies into national development plans, subsidizing internet access in backward regions, training the public's digital skills, and providing digital inclusive finance, the digital divide can be bridged,

promoting more sustainable and equitable regional development. Third, we find some feasible contextualized digital transformation schemes, namely the four models revealed above. These schemes can provide references for policy-making on coordinated regional economic development in economies with similar contextual characteristics. The key policy implication is that successfully reducing regional disparities depends on adopting the right combination of digital initiatives tailored to specific economic contexts. We oppose static views of digital practices, including slogans of "configuration" or "tailoring to local conditions" that remain at the abstract level.

This paper acknowledges some limitations that require future efforts. First, due to significant variations in digitalization statistics across economies, variable measurement needs to maintain a difficult balance between data availability, sample size, and scientific validity. For example, although datasets from OECD would provide superior metrics for assessing digital sectors and technological innovations, these resources were not utilized because they fail to capture numerous emerging and developing economies. We anticipate that scholars will eventually develop metrics for digitalization that are both more inclusive and standardized across regions. Second, due to the difficulty of measuring sub-national data, we did not analyze the impact of digital inequality within economies in detail, mainly constructing digital inclusion indicators through national-level digital facility usage and digital skills. In the future, attempts can be made to construct large-N sub-national digitalization datasets to deepen the understanding of related issues. Other limitations are related to the methods used. For example, QCA faces restrictions regarding the quantity of conditional parameters that can be simultaneously analyzed. Balancing theoretical comprehensiveness with methodological feasibility while consolidating various factors into coherent conceptual groupings remains a task for future research. Additionally, since external anchors were unavailable, variables were calibrated based on sample distributions in the study.

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Author contributions

Shuigen Hu was responsible for conceiving the research topic and design, and also contributed to the writing of the initial draft. Yulong Jie participated in the data collection, contributed to the research design, and assisted in writing the initial draft. Siling Zhu was in charge of data analysis and contributed to the writing of the manuscript.

Disclosure statement

The authors declare that there are no competing interests to declare in relation to the manuscript. This statement is made to confirm that there have been no financial, personal, or professional relationships or affiliations that could be viewed as potential conflicts of interest affecting the objectivity, integrity, or interpretation of the research presented.

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