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Digital Transformation in ASEAN Economies: A Temporal-Taxonomic Analysis of Structural Heterogeneity and Convergence Dynamics

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Abstract

This article presents a comparative assessment of digital transformation pathways in ASEAN economies, taking into account both the level and the structural composition of digitalization within the region. The study draws on internationally comparable data and advances an original temporal–taxonomic analytical approach based on the composite CMG indicator, which integrates three core dimensions of digital transformation: connectivity, market, and governance–sustainability-trust areas. The focus on Southeast Asian economies is substantively justified by the region's pronounced heterogeneity in economic development, institutional capacities, and digitalization outcomes, combined with its strategic importance as one of the most dynamic emerging regions where digital transformation plays a pivotal role in shaping long-term growth trajectories and structural convergence prospects. The novelty of the research lies in the construction and application of the research tool: the CMG indicator—as a transparent and replicable measurement framework designed to enable the simultaneous analysis of the intensity of digitalization and its internal structure. Such an approach addresses key limitations of existing digitalization indicators when employed in dynamic and structure-oriented comparative research. Moreover, the integration of synthetic measurement techniques with cluster analysis allows for the identification of distinct digitalization profiles among ASEAN countries and for tracing their differentiated development trajectories under conditions of accelerated digital transformation. The results reveal substantial heterogeneity in digital transformation processes across the region, arising from the combined influence of differences in economic development levels, institutional conditions, market structures, and regulatory frameworks, which jointly shape national digitalization trajectories. The analysis identifies both advanced and relatively stabilized digitalization profiles, as well as catch-up pathways characterized by rapid improvements in digital infrastructure and regulatory environments. The conducted research demonstrates a clear value added resulting from the proposed coherent measurement framework, which enables the analysis of digital transformation from both temporal and taxonomic perspectives and provides new empirical evidence on emerging economies. The findings also have practical relevance, offering insights for the

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design of context-sensitive digital strategies aimed at reducing structural disparities and supporting inclusive and sustainable digital development in Southeast Asia.

Keywords: digital transformation; ASEAN; taxonomic clustering; digital indicators; regional development

1. Introduction

In the era of the digital revolution, Economy 4.0 is progressively taking shape as the defining architecture of contemporary socioeconomic transformation, driven by the convergence of advanced digital technologies, cyber-physical systems, artificial intelligence, and pervasive connectivity [1]. The revolution 4.0 is not only a grass-roots business-industrial initiative but a revolution requiring the integration of horizontal and vertical linkages across value chains and production systems [2]. However, the foundations of its functioning and development are closely linked to the enabling environment provided by the State.

While the Fourth Industrial Revolution is frequently portrayed as a global, technology-driven transformation, its pace and outcomes remain highly uneven across countries [3–5]. This heterogeneity is shaped not only by market dynamics but also by differences in state capacity, institutional arrangements, and public policy priorities that enable or constrain the diffusion of digital technologies and cyber-physical systems [6–8]. Consequently, in the context of Economy 4.0, assessing how countries differ in their levels and structural profiles of digitalization becomes a necessary step for understanding the readiness of national economies and for deriving meaningful policy implications.

In this context, the State assumes a pivotal role, distinguished not merely as an administrative entity but as an institutional architecture that integrates political, social, and economic dimensions. The concept of the State is anchored in three foundational components: a defined territory that establishes its spatial and jurisdictional boundaries; a system of law and governance that embodies authority, regulatory power, and institutional legitimacy; and a population or society, whose collective aspirations, capacities, and socioeconomic participation shape both the demand for and responsiveness to public policies [9].

Based on a preliminary review of the scientific literature and publicly available empirical studies, we identify a research gap regarding the comparative assessment of digitalization levels in Southeast Asian countries, including the identification of structural similarities and differences across ASEAN member states [10–16]. For the purposes of this study, we use the term "region" consistently to refer to Southeast Asia as a macro-regional set of sovereign economies associated with ASEAN and treated as a single analytical unit in our comparative assessment. Importantly, while previous studies and regional reports have examined digital development and digitalization disparities in ASEAN, existing evidence remains fragmented with respect to the applied measurement frameworks, cross-country structural classification, and the incorporation of a consistent temporal perspective.

However, comparative, structure-oriented evidence on digitalization heterogeneity within Southeast Asia remains limited, which makes it difficult to draw robust conclusions about similarities and divergences among ASEAN member states. In particular, prior research rarely combines a unified composite measurement of digitalization with a taxonomic approach that allows for the identification of structural digitalization profiles and their evolution over time.

Within this scope, a research problem has also been formulated in the form of the following question: *Are the digitalization levels of Southeast Asian countries similar, or are there specific differences between them and, if so, are they significant?*

In this paper, the research was undertaken to identify factors enabling the development of digitalization of economies in ASEAN countries, currently creating the "world's largest free trade area", and constituting a group of 10 countries with a population exceeding 600 million people and an estimated USD 100 billion in revenues from the digital economy in 2023, which is growing at 27% CAGR since 2021 [17]. The clear digital transformation of ASEAN countries is evidenced by data showing that in 2015 the digital economy of this region accounted for 1.3% of ASEAN's GDP and in 2019 already 3.7%, with an assumed 8.5% in 2025 [18].

Despite these impressive aggregate gains, significant intra-regional disparities persist in the levels and trajectories of digitalization across ASEAN member states. Therefore, the aim of this article is to analyse and assess the heterogeneity in digitalization levels among Southeast Asian countries, identify structural similarities and divergences, and formulate strategic inferences.

To achieve this aim, the study contributes by estimating a CMG composite digitalization index based on a unified measurement framework and by applying a temporal–taxonomic approach that combines synthetic indicators with clustering techniques to map digital transformation pathways in ASEAN countries.

This approach is motivated by recent literature, which clearly highlights significant inconsistencies in the measurement of digitalization across countries, pointing to important methodological challenges. In particular, studies by Bruno et al. [19] indicate issues of internal coherence in composite indices, while Choczyńska et al. [20] show that differences in index construction and weighting schemes lead to discrepancies in country rankings and clustering results. Consequently, the choice of a specific index may influence the interpretation of digital development levels and cross-country comparisons. These findings suggest certain methodological limitations and point to the need for more consistent and transparent measurement frameworks.

In response to these challenges, this study proposes the CMG indicator, which integrates three dimensions of digital transformation: connectivity, market, and GST (governance, sustainability and trust) areas. This framework enables both a balanced and structurally decomposable assessment of digitalization, thereby supporting more nuanced comparative analysis across ASEAN economies.

Accordingly, the primary contribution of this study is methodological, namely the development and application of the CMG composite index as a unified, transparent, and replicable measurement framework for assessing digitalisation. The empirical contribution follows from applying this framework to ASEAN countries, providing new evidence on cross-country heterogeneity and structural digitalisation patterns.

This scientific article is divided into several logically interconnected sections, structured according to core principles of scholarly investigation—including analysis and synthesis, deductive and inductive reasoning, comparative evaluation, and generalized inference.

2. Digital Economy and Digital Transformation in ASEAN Member States: Conceptual Foundations and Related Empirical Study

This section is structured around three interrelated streams:

1. Conceptual foundations of the digital economy and digital transformation,
2. Structural Heterogeneity and the Convergence of Digitalization in Developing Countries: A Theoretical–Cognitive Perspective
3. Empirical evidence on digitalization and disparities among ASEAN countries, and

4. Methodological approaches to measuring and comparing national digitalization levels.

The digital economy includes all economic processes, transactions, interactions, and activities based on digital technologies [21]. It is an ecosystem in which consumers, businesses, and governments operate within a digital society, co-creating value across multiple domains. The transformation toward Economy 4.0, understood as a digitally enabled economic system, requires both bottom-up and top-down actions, including [22–28]:

(1) establishing regulatory and legal frameworks addressing data protection, liability, and trade restrictions;
(2) standardization and reference architectures enabling interoperability;
(3) ensuring security and reliability in products, workplaces, and data transmission;
(4) developing digital infrastructure such as broadband networks;
(5) managing complex systems using appropriate analytical models and tools;
(6) redesigning work organization in response to real-time digital tasks;
(7) supporting continuous skills development; and
(8) promoting resource efficiency within the context of the Fourth Industrial Revolution.

Digital infrastructure constitutes the backbone of both the digital economy and digital society [29,30]. In parallel, the digital economy is frequently operationalized as the contribution of digital products and digitally intensive industries to national GDP [31].

Digital transformation is commonly conceptualized as a staged process encompassing digitization (conversion of analog data into digital form), digitalization (integration of digital tools into organizational and economic processes), and full digital transformation (framed as a broader, strategic and systemic reconfiguration of business models, institutions, and socio-economic structures) [32,33]. This conceptual distinction is widely adopted in the literature and provides an analytical basis for assessing national digital readiness.

However, the trajectory and outcomes of digital transformation are not uniform across countries, as they are significantly conditioned by structural heterogeneity. In the economic development literature, it refers to persistent differences in economic structures, institutional quality, and levels of technological readiness across countries, which in turn lead to diverse trajectories of growth and modernization [34]. In the context of digitalization, this heterogeneity is reflected not only in the overall level of technological development but also in the internal configuration of digital ecosystems [35]. Existing research emphasizes that digital transformation is inherently uneven and path-dependent, reflecting historical trajectories, institutional quality, and public policy frameworks [34,36]. In the ASEAN region, these disparities are particularly pronounced. Consequently, digital transformation in this region cannot be considered a uniform process; rather, it unfolds as a set of structurally differentiated development paths shaped by diverse configurations of infrastructure, markets, and institutional systems [37].

An important complement to this perspective is the concept of convergence, which enables the analysis of changes over time. In light of economic growth theory and the literature on technology diffusion, digital convergence may occur through mechanisms such as knowledge transfer, inflows of foreign direct investment, regional integration, and policy harmonisation. In the ASEAN context, integration processes and initiatives supporting the development of the digital economy contribute to the gradual reduction in disparities among member states.

However, available studies indicate that this convergence is partial and differentiated in nature. It tends to occur relatively quickly in infrastructural domains, such as internet access, where technology diffusion is more intensive. In contrast, progress is considerably slower in more advanced dimensions, including the development of digital markets and institutional quality, where significant disparities persist [38]. As a result, alongside processes of convergence, enduring elements of divergence can also be observed. Empirical studies on ASEAN countries confirm this ambiguity, while also highlighting the persistence of the “digital divide.” This phenomenon encompasses not only disparities in access to infrastructure, but also differences in digital skills and in the capacity to generate economic value from technology [39].

As a result, the interaction between structural heterogeneity and convergence processes generates complex development dynamics. On the one hand, initial differences create conditions conducive to catch-up effects; on the other hand, persistent institutional constraints may hinder this process. Ultimately, this leads to the coexistence of convergence and divergence across different dimensions of digitalization [38].

From an empirical perspective, ASEAN has emerged as one of the most dynamic regions for digital transformation [39,40]. Comprising ten member states with a combined population exceeding 680 million and a GDP of nearly USD 3.2 trillion, the region is projected to become the world’s fourth-largest economy by 2030 [41,42]. The Asian Development Bank estimates that digitalization could generate an additional USD 1 trillion in ASEAN GDP by 2025, provided that investments in infrastructure, skills, and governance frameworks are sustained [31].

However, digital transformation trajectories across ASEAN remain highly uneven [37–49]. While countries such as Singapore and Malaysia have developed advanced digital and high-technology sectors, others—such as Cambodia, Lao PDR, and Myanmar—continue to face structural constraints related to infrastructure, skills, and institutional capacity [50,51]. These differences are further reflected in access to and usage of digital technologies. Internet penetration ranges from over 95% in Brunei to below 35% in Lao PDR [52], while average internet speed varies significantly across the region.

The literature consistently identifies the digital divide as a multidimensional phenomenon encompassing disparities in access, usage, and performance [53,54]. Empirical studies document not only cross-country gaps but also substantial within-country disparities across regions and socio-economic groups. For example, Wati et al. [55] highlight persistent digital skills gaps in Indonesia and link them to regional development indicators. Similar patterns are observed in patent activity, innovation capacity, and digital human capital across ASEAN economies [56].

At the policy level, regional initiatives such as the ASEAN Digital Integration Framework seek to promote regulatory harmonization, cybersecurity, digital innovation, and sustainable technology adoption [27,57]. Nevertheless, the literature also points to ongoing regulatory fragmentation and uneven institutional capacity, which may constrain cohesive regional digital development.

Methodologically, recent studies increasingly emphasize the need for multidimensional measurement approaches to capture the complexity of digital transformation [58–60]. Composite indicators, taxonomic methods, and clustering techniques are proposed as alternatives to single-index assessments, allowing for more granular comparisons of national digitalization profiles and development trajectories. These approaches are particularly relevant in heterogeneous regions such as ASEAN, where countries differ substantially in economic structure and institutional context.

A number of international and regional indicators have been developed to assess digitalisation and ICT development and are widely used for cross-country benchmarking. Prominent examples include the Digital Adoption Index (DAI) developed by the World Bank, which captures digital adoption across people, government, and business [61], the ICT Development Index (IDI) proposed by the International Telecommunication Union as a long-standing measure of ICT development and the digital divide [62,63], and the E-Government Development Index (EGDI), which focuses on the maturity of digital government and public digital services of the United Nations Member States [64]. In the ASEAN context, regional benchmarking initiatives such as the ASEAN Digital Integration Index (ADII) have been introduced to monitor progress toward digital integration and policy harmonisation within the region [65].

While these indices have significantly advanced comparative digitalisation research, they differ in conceptual scope, measurement objectives, and data architecture. The DAI is designed as a broad adoption-oriented measure with strong global comparability, but it is not intended to identify structural digitalisation profiles or to support taxonomic classification over time [66]. The EGDI concentrates on digital government readiness and therefore does not provide a comprehensive assessment of digital economy development sensu largo [64]. Similarly, the ADII primarily serves as a policy benchmarking tool aligned with ASEAN's digital integration agenda rather than as a compact composite index explicitly constructed for longitudinal and cluster-based analysis of national digitalisation trajectories [65]. Against this background, the CMG index is designed to complement rather than replace existing indicators. Its contribution lies in providing a transparent and replicable composite measurement framework, grounded in internationally comparable ITU data, consistently implemented for ASEAN countries over 2017–2022, and directly compatible with a temporal–taxonomic analytical approach. This design enables the simultaneous assessment of overall digitalisation levels and the identification of structural digitalisation profiles, addressing limitations observed in existing indices when applied to longitudinal clustering and pathway analysis [20,63,65,67]. This overview of existing indices and their respective measurement logics further highlights the need for a consistent, multidimensional, and longitudinally applicable framework to compare ASEAN countries and to identify structural digitalisation profiles.

Comparison of the CMG Index with Selected Digitalization Indices

In the table below (Table 1), a comparative overview of the selected indices DAI, IDI, EGDI, and ADII is presented in relation to the CMG index, taking into account the adopted comparative criteria.

The comparative analysis (see Table 1) of existing digitalization indices highlights a set of structural and conceptual limitations that justify the development of the CMG index.

First, most widely used indices—such as DAI, IDI, and EGDI—are either narrowly focused (e.g., ICT adoption, infrastructure, or public administration) or designed around a single analytical dimension. As a result, they do not fully capture digitalization as a systemic phenomenon encompassing the interaction between infrastructure, markets, and governance or management.

Second, although composite indices such as ADII adopt a more policy-oriented and multi-pillar approach, they remain geographically or institutionally bounded (e.g., ASEAN-specific) and are not fully generalizable for global comparative analysis.

In contrast, the CMG index introduces a systemic and structural framework, explicitly integrating three interdependent dimensions: Connectivity (infrastructure), Market (digital economy activity), and GST (governance, sustainability and trust). This allows for a more balanced representation of both supply-side and demand-side factors, as well as institutional conditions shaping digital transformation.

Furthermore, the CMG index enables structural decomposition of digitalization, rather than limiting analysis to aggregate levels of adoption or development. This provides deeper analytical value for identifying bottlenecks and asymmetries between infrastructural readiness, market maturity, and institutional capacity.

Finally, the use of a transparent and symmetric weighting scheme enhances interpretability and comparability while maintaining methodological simplicity.

Table 1. A Comparative Framework of Selected Digitalization Indices.

Criterion	CMG (Author's Index)	DAI (World Bank)	IDI (ITU)	EGDI (UN)	ADII (ASEAN)
Conceptual approach to index construction	Structural, equal-weight domains	Three user groups of the economy	Multidimensional framework	Three-component public sector model	Multi-pillar, policy-oriented composite approach
Purpose of the index	Analysis of the level and structure of digitalization	Measurement of digital technology adoption	Assessment of ICT development and digital divides	Evaluation of e-government development	Assessment of digital integration and policy alignment in ASEAN
Nature of the index	Structural-analytical	Adoption-oriented	ICT development-oriented	Sector-specific (public administration)	Policy-strategic
Main components	Connectivity, Market, GST (Governance, Sustainability and Trust)	People, Business, Government	Access, Use, Skills	Infrastructure, Human Capital, Online Services	Digital trade, regulations, payments, innovation, infrastructure, etc.
Treatment of infrastructure	Central element	Central element	Central element	Central element	Central element
Treatment of digital market	Explicit (Market)	Present (Business)	Present	Not explicitly included	Partially included within pillars
Treatment of institutions and regulation	Explicit (GST)	Partially included (Government)	Present	Strong emphasis	Key structural component
Aggregation method	Weighted sum (equal weights)	Simple average of three sub-indices	Aggregation of components	Aggregation of components	Multi-pillar aggregation
Role of weights	Equal weighting (1/3)	Equal weighting (mean-based)	Methodologically determined weights	Equal weighting (OSI; HCI; TII)	Heterogeneous weighting scheme
Scope of analysis	Economy as a system (infrastructure–market–institutions)	Technology adoption	ICT development	Public administration	Digital ecosystem integration
Ability to analyse digitalization structure	High	Limited	Limited	Limited	Partial
Cross-country comparability	Yes	Yes	Yes	Yes	limited to ASEAN countries

Source: Authors' own analysis.

In summary, it should be emphasized that the CMG index fills a methodological gap in the existing literature by offering a holistic, system-based, and analytically decomposable measure of digitalization, which allows for more comprehensive cross-country comparisons and more precise policy diagnosis than existing indices.

At this stage of the research, the primary objective is the development and internal validation of the CMG index as a new conceptual framework for measuring digitalization. The focus is placed on the construction of the indicator structure, the selection of variables, and the determination of internal weighting schemes based on a combination of PCA results and expert judgment.

A full comparative analysis with existing digitalization indices (DAI, IDI, EGDI, and ADII) is deliberately reserved for a subsequent stage of the research. This decision is justified by methodological considerations, as benchmarking a newly constructed composite indicator prior to its full internal validation may lead to biased or premature conclusions.

Taken together, the reviewed literature suggests that digital transformation in ASEAN is shaped by infrastructural readiness, institutional capacity, and governance frameworks, while simultaneously exhibiting pronounced cross-country heterogeneity. However, despite a growing body of descriptive and policy-oriented studies, there remains limited empirical evidence that systematically compares ASEAN countries using unified measurement frameworks and structural classifications. This gap provides the conceptual basis for the formulation of the study hypotheses, which focus on testing whether statistically significant differences and identifiable structural similarities in digitalization levels exist among ASEAN member states.

Building on this gap, the present study employs synthetic indicators and taxonomic clustering methods to analyse digital transformation trajectories in ASEAN countries over the period 2017–2022, thereby contributing to the empirical literature on comparative digital economy analysis in emerging regions.

3. Materials and Methods

3.1. The Research Procedure and Assumptions of the Scientific Work

The implementation of scientific research on "Comparative Digital Transformation of the ASEAN Economies. Structure, Dynamics and Developmental Implications from a Temporal-Taxonomic Perspective" involved the following activities and actions, allowing it to be carried out by adopting the following research procedure (see Figure 1).

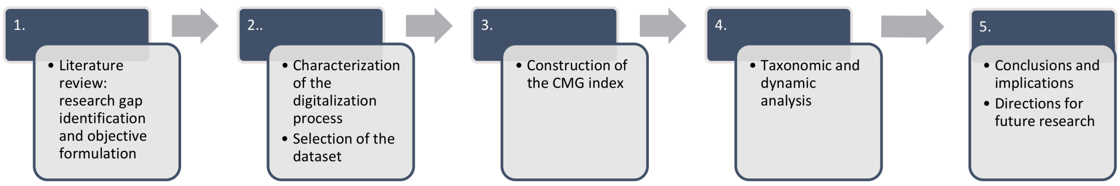

Figure 1. The scheme of research methodology. Source: Authors' own analysis.

The research on the comparative digital transformation of the ASEAN follows a structured analytical framework designed to ensure consistency between the research objectives, data, and applied methods (see Figure 1).

The study begins with the definition of the research scope, including the formulation of the topic, identification of the research gap, and specification of the research problem, objectives, and the temporal and spatial coverage of the analysis. On this basis, the research hypotheses are developed.

Subsequently, a critical review of the relevant literature is conducted, which provides the conceptual and theoretical foundation for the empirical analysis. This stage allows for the identification of key determinants of digital transformation in ASEAN countries and highlights existing heterogeneity across the region.

The methodological design of the study is then specified, including the selection of the analytical approach, data sources, and the identification of potential methodological limitations.

The empirical part of the study is based on the implementation of the proposed methodological framework and the construction of composite indicators used to assess digital transformation across countries and over time.

The final stages of the study involve the interpretation and synthesis of empirical results, including the formulation of conclusions and discussion of their implications.

Directions for future research are identified based on observed limitations and emerging research gaps.

The lack of research dedicated to the issue of the digitalization level of Southeast Asian countries, together with the identification of similarities of structures in this regard were identified as the research gap. To fill the research gap thus identified, the choice was made to use clustering within cluster analysis as part of the statistical methods, which makes it possible to divide groups of countries into so-called superior and inferior clusters.

The research problem was formulated in the form of the following question: *Are the digitalization levels of Southeast Asian countries similar or are there specific differences between them and, if so, are they significant?*

With the research gap thus identified and the research problem formulated, the authors of the paper defined the objective of this research paper, which is to analyze and assess the heterogeneity in digitalization levels among Southeast Asian countries, identify structural similarities and divergences and formulate strategic inferences.

The subject of the research relates directly to its objective, defined above, and that is to analyze and assess the digitalization levels of Southeast Asian countries.

The object of the research includes the following Southeast Asian countries: Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar (Burma), Philippines, Singapore, Thailand, and Vietnam, which together form one region centered around the Association of Southeast Asian Nations (ASEAN).

The spatial scope of the research, on the other hand, takes into account the spatial-geographical location of the aforementioned ten countries, which form one region and whose countries belong to the Association of Southeast Asian Nations (ASEAN). It is worth mentioning at this point that the objectives behind the creation and development of ASEAN include:

- Economic aspects: to accelerate economic growth in the region;
- Social and cultural aspects: social progress and cultural development in the region;
- Legal and security aspects in the region: to promote regional peace and stability through abiding respect for justice and the rule of law in the relationship among countries in the region and adherence to the principles of the United Nations Charter.

The choice of the ASEAN countries was not random, but is related to their importance and the role they play in the global economy. It is a region with a population of 686 million as of 2024, i.e., more than 8% of the world's population, and real GDP growth of 4.6%, i.e., 4.08 thousand billion US dollars in current prices, which is just under 4% of the GDP share of the world economy in 2024 [66–68].

The strength of these countries is their dynamic economic development, which began at the turn of the 1990s, making them the so-called "Asian tigers" that not only pursue intra-regional cooperation but also meet the needs and opportunities in this respect through cooperation with countries in Europe, America, the rest of Asia, Australia and other regions of the world.

It is worth noting at this point that in 2020, the foreign ministers of the European Union and ASEAN countries decided to elevate cooperation between the EU and ASEAN to the level of a strategic partnership [69], which, also in the European context, speaks in favour of conducting scientific research on the horizon of mutual cooperation and development of scientific thought between scientists from these regions.

The temporal scope of the research covers the period between 2017 and 2022, which was adopted due to the availability of data on the topic of analysis and assessment of the digitalization level of the analyzed economies of the ASEAN countries.

The adopted study period covering the years 2017–2022 was selected deliberately and is substantively justified:

First, it represents the longest continuous time span for which internationally comparable ITU data are available for all ASEAN countries included in the analysis, which is essential for ensuring the reliability of the dynamic assessment.

Second, this period corresponds to an intensification of digitalization processes in Southeast Asia, associated both with the implementation of national and regional digital strategies and with the growing role of the digital economy in the GDP structure of ASEAN countries.

An additional justification for selecting this time frame is that it encompasses the years immediately preceding the COVID-19 pandemic as well as the period of its impact, both of which significantly influenced the pace and directions of digitalization, particularly in the areas of connectivity, e-services, and digital regulation. Consequently, the analysis of changes between 2017 and 2022 allows for capturing both long-term structural trends and systemic responses to an external economic shock.

At the same time, the six-year time horizon is sufficiently long to observe meaningful changes in both the level and structure of digitalization, while remaining concise enough to preserve methodological coherence and comparability of results. As a result, the selected study period enables a reliable identification of digital transformation trajectories and an assessment of the degree of convergence and divergence among ASEAN countries.

In the study, the following **research hypotheses** (RHs) were formulated:

RH1. *ASEAN member states differ distinctly in their levels of digitalization over the period 2017–2022.*

RH2. *ASEAN countries can be classified into distinct clusters characterized by high, medium, and low levels of digitalization.*

RH3. *Higher levels of digitalization are positively associated with higher levels of economic development, industrialization, and social development among ASEAN countries.*

Taking the above hypotheses into account, it should be noted that the scholarly literature—as demonstrated earlier—emphasizes that digital transformation is inherently uneven and contingent upon structural and institutional conditions, which leads to persistent disparities among countries at different stages of development. Consequently, in regions such as ASEAN, where economies with markedly diverse levels of development coexist, one should expect pronounced differences in the level of digitalization. This provides a direct justification for the hypothesis positing distinctly differentiated levels of digitalization across countries. Moreover—as emphasized in the theoretical section of the study—a structural approach to the analysis of digitalization indicates that differences between countries are not limited to the overall index level but also encompass its internal composition, namely the relationships among infrastructure, markets, and institutions. Such a multidimensional perspective leads to the identification of relatively homogeneous groups of countries with similar development profiles ("clusters"). Under conditions of substantial structural heterogeneity within ASEAN, this implies the possibility of distinguishing groups of countries with comparable digital configurations, which is reflected in the hypothesis positing the existence of clusters of countries characterized by high, medium, and low levels of digitalization. It is also worth emphasizing that the literature on convergence indicates that the level of digital development is strongly associated with the overall level of economic development and the quality of institutions. Mechanisms such as technology diffusion, foreign direct investment, and economic integration foster "catch-up" processes; however, their effectiveness depends on the absorptive capacities of an economy, which in turn are correlated with GDP levels, economic structure, and human capital. In the context of ASEAN, this implies that more advanced economies should exhibit higher levels of digitalization, which constitutes the basis for the hypothesis positing a positive relationship between the level of digitalization and the level of socio-economic development.

RH1 is tested through a comparative analysis of the synthetic digitalization index across ASEAN countries. RH2 is examined using hierarchical cluster analysis based on Ward's method, complemented by the nonparametric Kruskal–Wallis test to assess differences between the identified groups. RH3 is evaluated by analysing the relationships between the level of digitalization and selected socio-economic development indicators.

3.2. Implications for Measurement Framework Design Considering the Limitations of Existing Digitalization Indicators

The development of the proprietary CMG indicator (Connectivity–Market–GST) was motivated by the observed limitations of existing digitalization indices, such as the IDI, DAI, EGDI, and ADII, which—despite their high informational value—are not always directly applicable to temporal analyses or to the taxonomic classification of countries [63,64]. Available indices differ in their conceptual scope, measurement objectives, and data architecture, which may hinder their use in coherent, multi-year comparative studies covering a homogeneous set of countries. Moreover, most of these indices focus primarily on the overall level of digitalization, paying less attention to its internal structure, thereby limiting the possibility of identifying distinct digitalization profiles and analyzing their evolution over time.

The CMG indicator was therefore designed as a complementary tool to existing indices. Its construction is based exclusively on internationally comparable ITU data and incorporates three key dimensions of digital transformation: infrastructural, market-related, and institutional–regulatory [70]. The application of the standardized sums method and equal weights assigned to the sub-indicators enhances interpretative transparency and enables the use of the index in cluster analysis.

The proprietary nature of the CMG indicator allowed it to be tailored to the requirements of dynamic and structural comparative analysis, thereby providing a foundation for examining similarities and differences in digital transformation patterns among ASEAN countries.

3.3. Sources of Data, Construction of Research Tool and Limitations of the Research

3.3.1. Materials, Data Sources and Rationale for Selection

The data were obtained from the *World Telecommunication/ICT Indicators Database* maintained by the International Telecommunication Union (ITU), a specialized agency of the United Nations responsible for information and communication technologies. The ITU database includes more than 170 indicators describing the development of ICT and constitutes an internationally comparable and regularly updated source. It encompasses both quantitative and qualitative measures (including regulatory status and the existence of legal frameworks), thereby enabling a multidimensional assessment of digitalization.

Diagnostic Variables

From the set of ITU indicators, a total of 23 diagnostic variables were selected through an expert-based approach, consistent with the substantive scope of three dimensions of digitalization: 8 variables for the Connectivity (C) domain, 8 for the Markets (M) domain, and 7 for the Governance, Sustainability and Trust (GST) domain. All variables are classified as stimulants, meaning that higher values correspond to a higher level of digital development. The complete list of variables is presented in Table 2.

Table 2. Diagnostic variables of the CMG index, their characteristics, and partial weights.

No.	Diagnostic Variable (ITU)	Character	Unit	Weight w_j
Connectivity (C)—8 variables				
1	Households with a computer	Stimulant	%	0.05
2	Households with Internet access at home	Stimulant	%	0.20
3	Fixed-telephone subscriptions	Stimulant	per 100 inhabitants	0.05
4	Mobile-cellular subscriptions	Stimulant	per 100 inhabitants	0.10
5	Population coverage, by mobile network technology	Stimulant	%	0.10
6	Fixed-broadband subscriptions	Stimulant	per 100 inhabitants	0.10
7	Active mobile-broadband subscriptions	Stimulant	per 100 inhabitants	0.10
8	Individuals using the Internet	Stimulant	%	0.30
Markets (M)—8 variables				
9	Wireless Local Loop (competition status)	stimulant *	code 0-1	0.12
10	Local fixed line services (competition status)	stimulant *	code 0-1	0.12
11	Mobile Broadband (competition status)	stimulant *	code 0-1	0.14
12	Annual investment in telecommunication services	Stimulant	USD	0.14
13	National broadband plan exists	stimulant *	0/1	0.14
14	Revenue from mobile networks	Stimulant	USD	0.12
15	Revenue from all telecommunication services	Stimulant	USD	0.12
16	Full-time equivalent telecommunication employees	Stimulant	FTE	0.10
GST (Governance, Sustainability and Trust)—7 variables				
17	Consumer protection authority	stimulant *	0/1	0.15
18	ICT Policy	stimulant *	0/1	0.15
19	Regulatory framework for e-Applications	stimulant *	0/1	0.15
20	Individuals with ICT skills: software installation/configuration	stimulant	%	0.10
21	Individuals with ICT skills: computer programming	stimulant	%	0.15
22	ICT consumer protection legislation	stimulant *	0/1	0.15
23	Cybersecurity legislation/regulation exist	stimulant *	0/1	0.15

* a qualitative variable transformed into a quantitative form. The weights sum to unity within each domain. Source: own elaboration on base: https://www.itu.int/en/ITU-D/Statistics/ (accessed on 10 January 2026).

Coding of Qualitative and Binary Variables

Dichotomous variables of the "Yes/No" type (i.e., the existence of a consumer protection authority, ICT policy, a regulatory framework for e-applications, a national broadband plan, ICT consumer protection legislation, and cybersecurity regulations) were recoded into binary variables by assigning a value of 1 to "Yes" (a desirable feature, i.e., a stimulant) and 0 to "No".

Variables describing the status of market competition (Wireless Local Loop, Local fixed-line services, Mobile Broadband) are ordinal in nature and were encoded monotonically according to the degree of market competitiveness as follows: Monopoly = 0; Partial competition = 0.5; Full competition = 1. Cases labeled as "N/A" were treated as missing values and subjected to imputation.

The variables quantified in this manner were subsequently incorporated into the standardization procedure on an equal footing with quantitative variables.

Missing Data and Imputation

Missing data were considered in two dimensions. First, for missing values in time series of individual variables (i.e., the absence of an observation for a given year in the presence of values for adjacent years), linear interpolation was applied. Second, for cross-sectional missing values (i.e., the absence of an observation for a given country when the same variable was available for other countries), imputation was performed using the k-nearest neighbors (k-NN) method, in which the missing value is estimated as a weighted average of the values of the k closest observations, where proximity is defined in terms of Euclidean distance in the space of available standardized variables.

A value of k = 3 was adopted, which, given a sample of ten countries in each year, represents a compromise between bias (too small k) and excessive smoothing (too large k). This choice is consistent with recommendations for the k-NN method for small datasets [71].

3.3.2. Construction of the CMG Index

The synthetic digitalization index CMG (an acronym derived from the domains: Connectivity, Markets, and GST) enables the ranking of economies while simultaneously accounting for both the intensity and internal structure of digitalization. The overall index is defined as an aggregation of three sub-indices:

$$CMG_i = w_1 C_i + w_2 M_i + w_3 GST_i, w_1 = w_2 = w_3 = \frac{1}{3} \tag{1}$$

where C_i, M_i, and GST_i denote the values of the sub-indices for the i-th country, and w_1, w_2, w_3 are the weights assigned to the sub-indices. In the baseline variant, equal weights were adopted (their justification and sensitivity analysis are presented below).

3.3.3. Linear Ordering Using the Standardized Sum Method

The sub-indices C, M, and GST were constructed separately for each of the three sets of variables using linear ordering based on the standardized sum method. This is a non-pattern-based approach in multidimensional comparative analysis, originating from the taxonomic measure of development [72]. The procedure consists of the following steps:

Step 1. Identification of variable types (stimulant, destimulant, nominant) and transformation of all variables into stimulants. A destimulant is transformed by sign reversal:

$$x_{ij}^S = \max_i \{x_{ij}\} - x_{ij} \tag{2}$$

A nominant with nominal value n_j is transformed as:

$$x_{ij}^S = - \mid x_{ij} - n_j \mid \tag{3}$$

In the analyzed dataset, all variables are stimulants; thus, transformations (2)–(3) do not modify the data and are included for completeness.

Step 2. Standardization of variables to ensure comparability of units and magnitudes:

$$z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j}, s_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{ij} - \bar{x}_j)^2} \tag{4}$$

where $\bar{x}_j$ and s_j denote the mean and standard deviation of the j-th variable in a given year and domain.

Step 3. Construction of the synthetic variable as a weighted sum of standardized variables:

$$q_i = \sum_{j=1}^{m} w_j z_{ij} \tag{5}$$

Step 4. Determination of the theoretical pattern (maximum) and anti-pattern (minimum):

$$q_0^+ = \sum_{j=1}^{m} w_j z_{0j}^+, q_0^- = \sum_{j=1}^{m} w_j z_{0j}^- \tag{6}$$

where:

$$z_{0j}^+ = \max_i \{z_{ij}\}, z_{0j}^- = \min_i \{z_{ij}\}$$

Step 5. Normalization of sub-indices to the interval [0, 1] with respect to the pattern and anti-pattern:

$$C_i = \frac{q_i - q_0^-}{q_0^+ - q_0^-}, M_i = \frac{q_i - q_0^-}{q_0^+ - q_0^-}, GST_i = \frac{q_i - q_0^-}{q_0^+ - q_0^-} \tag{7}$$

A value of 0 indicates the lowest, and a value of 1 the highest position in the ranking. The sub-indices C, M, and GST, as well as the overall CMG index, take values within the interval $[0, 1]$, ensuring their direct comparability and suitability as input variables for cluster analysis.

3.3.4. Weight Selection, Sensitivity Analysis, and Ranking Robustness

Justification of the Baseline Weighting Scheme

The baseline scheme combines two levels of weighting. At the level of aggregating domains, equal weights were adopted (each of the domains C, M, and GST assigned a weight of 1/3). Equal weighting is recommended in the literature as a neutral and transparent solution in situations where there is no theoretical or empirical consensus regarding the relative importance of dimensions. It does not constitute an assumption of equal importance, but rather a deliberate decision to avoid introducing unjustified a priori preferences [73,74]. This approach enhances the interpretability of the index and its usefulness for classification purposes.

At the level of variables within domains, expert-based weights were applied, reflecting the relative importance of individual indicators for the contemporary measurement of digitalization (e.g., a higher weight assigned to actual Internet use by individuals compared to computer ownership in households stems from the fact that the former directly reflects effective participation in the digital economy, whereas the latter captures only potential access to equipment). However, the adopted weights should be treated as an assumption subject to verification; therefore, they were subjected to sensitivity analysis.

Alternative Weighting Schemes

To assess the impact of weighting choices on the results, in addition to the baseline scheme (equal/expert weights), two data-driven weighting schemes were constructed, both based on the internal structure of the data.

Weights Based on Principal Component Analysis (PCA)

The weight of a variable is determined proportionally to its contribution to the variance explained by the extracted principal components. This is calculated using squared factor loadings weighted by eigenvalues:

$$w_j = \frac{\sum_{k=1}^{p} \lambda_k a_{jk}^2}{\sum_{j=1}^{m} \sum_{k=1}^{p} \lambda_k a_{jk}^2} \tag{8}$$

where λ_k denotes the eigenvalue of the k-th component, a_{jk} is the loading of the j-th variable on the k-th component, and the summation is performed over $p\ components$ with eigenvalues greater than one.

Weights Based on Shannon Entropy

The weight of a variable is derived from the degree of dispersion of its values across objects (the greater the variability—i.e., the lower the entropy—the higher the informational weight):

$$e_j = \frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij},\ p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}},\ w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \tag{9}$$

where e_j denotes the entropy of the j-th variable, and p_{ij} represents the share of the i-th object in the total value of the j-th variable.

Ranking Robustness

For each weighting scheme (baseline, PCA, entropy), the CMG index and the resulting ranking of the ten countries were recalculated for both years. The agreement between rankings was assessed pairwise using Spearman's rank correlation coefficient, while the stability of index values was evaluated using Pearson's linear correlation coefficient. Additionally, following the uncertainty and sensitivity analysis framework for composite indicators [73], the range of ranking positions for each country across all considered variants is reported. Small positional changes (range 0–1) and high values of the ρ coefficient indicate that the ordering of countries is not an artifact of the adopted weighting scheme.

3.3.5. Validation of the CMG Index

The proposed CMG index was evaluated using two complementary validation procedures.

Comparative Assessment

The conceptual framework of the CMG index was compared with widely used digitalization indices, namely the ICT Development Index (IDI), the Digital Adoption Index (DAI), the E-Government Development Index (EGDI), and the ASEAN Digital Integration Index (ADII). The comparison, shown in Table 1, focused on their conceptual foundations, scope, principal dimensions, aggregation methods, and analytical capabilities. Particular attention was paid to the ability of the indices to capture the structural characteristics of digital transformation and their applicability to comparative taxonomic analysis.

Internal Consistency

The internal consistency of the CMG framework was assessed by analysing the relationships among the three sub-indices (Connectivity, Market, and GST) and between each sub-index and the overall CMG indicator. Cronbach's alpha coefficient was additionally calculated to evaluate the coherence of the composite measure

3.3.6. Taxonomic Classification—Hierarchical Cluster Analysis

To classify ASEAN countries according to the level and structure of digitalization, hierarchical agglomerative cluster analysis was applied. The procedure was conducted separately for 2017 and 2022, based on the values three sub-indices (C, M, GST).

Distance Measure and Linkage Method

The squared Euclidean distance was adopted as the measure of dissimilarity between objects:

$$d^2(x_a, x_b) = \sum_{j=1}^{m} (x_{aj} - x_{bj})^2 \tag{10}$$

Clustering was performed using Ward's method, in which, at each step, the pair of clusters is merged whose combination results in the smallest increase in the within-cluster sum of squares (i.e., minimizes the increase in within-cluster variance). This increase for merging clusters p and q is given by [75]:

$$\Delta_{pq} = \frac{n_p n_q}{n_p + n_q} \parallel \bar{x}_p - \bar{x}_q \parallel^2 \tag{11}$$

where n_p, n_q denote the sizes of the clusters, and $\bar{x}_p, \bar{x}_q$ represent their centroids.

Statistical Justification of the Number of Clusters

The number of clusters was determined based on a set of quantitative criteria:

Silhouette coefficient: for each object,

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}}, -1 \leq s(i) \leq 1 \tag{12}$$

where $a(i)$ is the average distance of object i to other objects within its own cluster, and $b(i)$ is the smallest average distance of object i to objects in another cluster. The average silhouette coefficient for the entire dataset, calculated for successive numbers of clusters, indicates the solution with the best separability [76].

Calinski–Harabasz index (variance ratio criterion): defined as the ratio of between-cluster to within-cluster sum of squares, normalized by degrees of freedom:

$$CH(k) = \frac{\mathrm{tr}(B_k)/(k-1)}{\mathrm{tr}(W_k)/(n-k)} \tag{13}$$

where B_k and W_k denote the between-cluster and within-cluster sum-of-squares matrices for a partition into k clusters, and n is the number of objects. The maximum value of $CH(k)$ indicates the optimal number of clusters [77].

Additionally, the agglomeration schedule (i.e., increases in linkage distances at successive stages, the so-called "elbow method") was analyzed. The combined application of these criteria provides a statistical—rather than purely visual—justification for the selected number of clusters. In cases where the criteria yield conflicting indications, the final decision is made taking into account interpretability and comparability of classifications across years.

3.3.7. Statistical Verification of Research Hypotheses

Formal testing procedures were introduced.

RH1—Differences in the level of digitalization across countries and clusters

Given the small sample size (ten countries) and the lack of assurance that the assumptions of normality and homogeneity of variances are met, the nonparametric Kruskal–Wallis test, based on ranks, was employed as the primary test:

$$H = \frac{12}{n(n+1)} \sum_{g=1}^{k} \frac{R_g^2}{n_g} - 3(n+1) \tag{14}$$

where R_g denotes the sum of ranks in the g-th cluster, n_g its size, n the total sample size, and k the number of clusters. Rejection of the null hypothesis of equal distributions confirms significant differentiation in the level of digitalization, thereby providing a statistical basis for the verification of RH1.

RH3—Relationship between digitalization and the level of economic development

Instead of a purely descriptive statement regarding the association between CMG and affluence, a quantitative assessment was introduced. The strength and direction of the relationship were measured using Pearson's linear correlation coefficient:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{15}$$

and, as a measure robust to deviations from linearity and to outliers, Spearman's rank correlation coefficient:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{16}$$

where d_i denotes the difference in ranks of the i-th object across the two orderings. For both coefficients, significance levels (p-values) are reported.

Additionally, a simple linear regression model was estimated to link the level of digitalization with the logarithm of GDP per capita (and, optionally, additional control variables, such as the share of trade in GDP):

$$CMG_i = \beta_0 + \beta_1 \ln(GDPpc_i) + \beta_2 X_i + \varepsilon_i \tag{17}$$

A statistically significant positive coefficient β_1 provides confirmation of RH3. Interpretative statements were adjusted to reflect the observed strength of the relationship, replacing categorical expressions (e.g., "strongly associated") with more cautious formulations grounded in the estimated coefficients and their statistical significance.

3.3.8. Analysis of Disparity Reduction (σ-Convergence)

As the notion of "convergence" had previously been used in an informal manner, without reference to the analytical framework of growth economics, a formal approach was introduced to provide a statistical basis for claims regarding the reduction of differences among countries. Specifically, the concept of σ-convergence was applied, measured by the coefficient of variation of the CMG index across countries over time:

$$V_t = \frac{1}{\overline{CMG}_t}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(CMG_{it} - \overline{CMG}_t\right)^2} \tag{18}$$

where $C\bar{M}G_t$ denotes the mean value of the index in year t, and n is the number of countries. A decrease in V_t between 2017 and 2022 indicates σ-convergence, i.e., a reduction in the dispersion of digitalization levels across the region [78]. This approach enables the formulation of precise conclusions regarding disparity reduction, rather than relying on general statements about "convergence."

3.3.9. Dynamic Index Calculation for Clusters

To assess changes in the level of digital transformation between 2017 and 2022, a dynamic index was calculated for the CMG index and its constituent dimensions. The dynamics indicator was defined as:

$$D_{i,j} = \frac{\bar{X}_{i,j,2022}}{\bar{X}_{i,j\ 2017}} \times 100 \tag{19}$$

where:

- $D_{i,j}$ denotes the dynamics index for cluster (i) and indicator (j),
- $\bar{X}_{i,j,2022}$ represents the mean value of indicator (j) in cluster (i) in 2022,
- $\bar{X}_{i,j,2017}$ represents the corresponding mean value in 2017.

Values above 100 indicate growth, whereas values below 100 indicate a decline relative to the base year (2017 = 100).

3.3.10. Software and Reproducibility

The calculation of sub-indices and the CMG index, missing data imputation, cluster analysis, validation procedures, and statistical tests were conducted using statistical software environments [79–81] and Python (version 3.12) [82,83]. Cluster analysis was performed using standard hierarchical clustering procedures (Ward's method, squared Euclidean distance). The silhouette coefficient and the Calinski–Harabasz index were computed using established cluster validation functions, while k-NN imputation was implemented via widely available libraries.

To ensure reproducibility, the random number generator seed was fixed and the versions of all software packages used in the analysis were documented.

The limitations of this research are connected above all with the limitations of the methods which were used in this research—they are described in detail in the literature on the subject of statistical methods [84–86] and also with the limitations of the data in the ITU database—the lack of completeness.

This research on the topic of digitalization levels of the ASEAN countries, with its analysis and assessment, inference and presentation of conclusions based on data from the ITU database, selected through expert selection, together with the development of a synthetic main indicator and synthetic partial indicators, is clearly of a pioneering nature, which is also confirmed by the earlier review of the literature on this topic area.

4. Results

This section of the article presents the results of the empirical research on the digital transformation of ASEAN countries, with particular emphasis on the level and structure of digitalization over the adopted time horizon. The analysis opens with the presentation of the values of the composite CMG indicator and its constituent components, which enables an assessment of the heterogeneity of the economies under study in both cross-sectional and dynamic terms. Subsequently, structural similarities and differences among ASEAN countries are identified and examined. The obtained results provide a solid basis for empirical interpretation and for formulating conclusions regarding the differentiated trajectories of digital transformation in Southeast Asia in the context of their socio-economic determinants.

4.1. Differences Between Countries

Figure 2 presents the values of the CMG indicator and its three sub-indicators for ASEAN countries in 2017 and 2022. The data indicate the existence of certain similarities, but also clear differences between the countries of the ASEAN group. Comparing the results for individual ASEAN countries over time, some economies show an improvement in the value of the main CMG indicator and its sub-indicators, whereas others register a decline.

This illustrates that despite belonging to one geographical, socio-cultural and civilization region such as ASEAN countries, their development, including its level, directions and dynamics of changes in their digital transformation, is not the same.

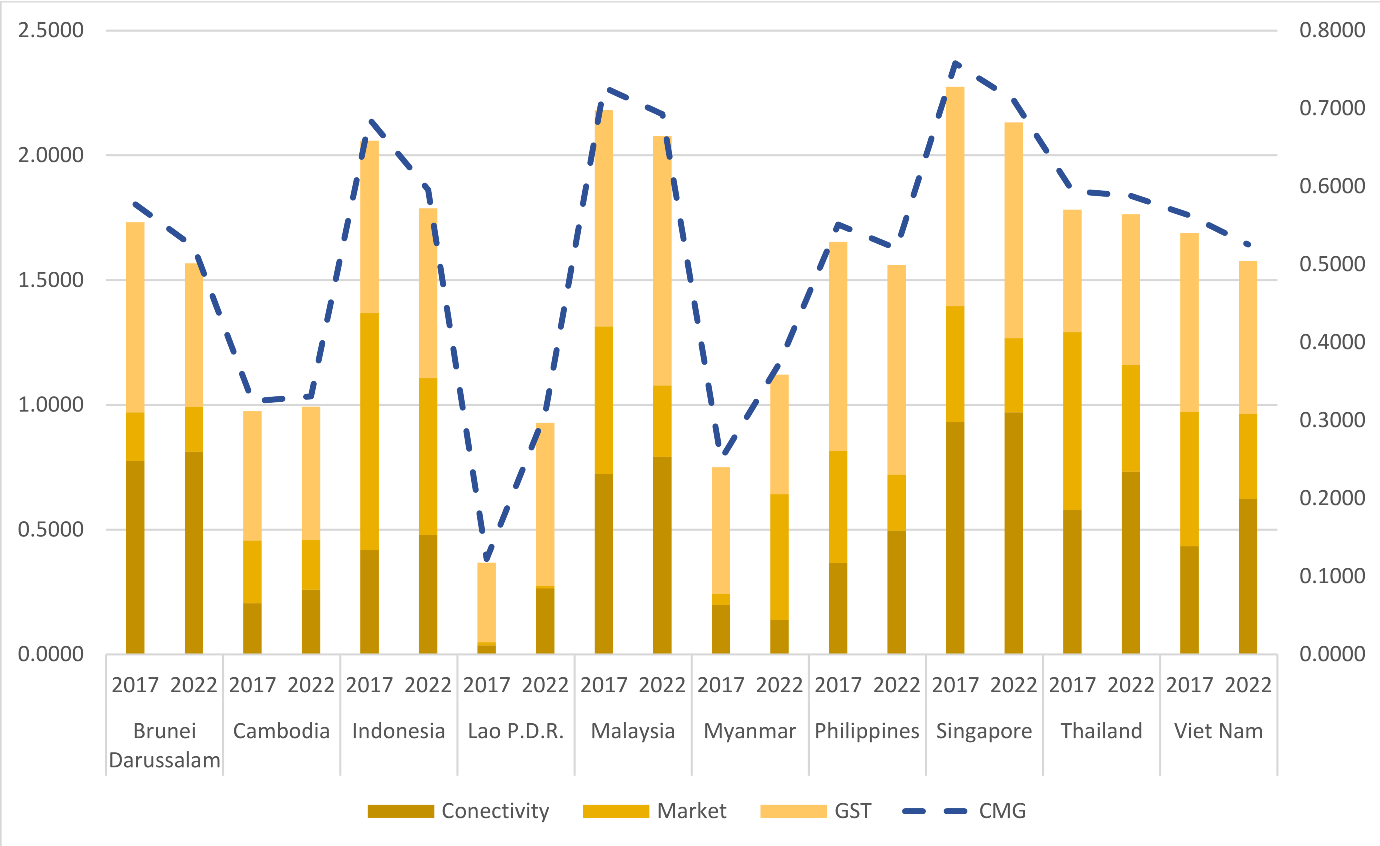

Figure 2. Comparison of Connectivity, Market, GST, and CMG index values across ASEAN countries in 2017 and 2022. Source: Authors' own analysis.

Figure 2 presents the values of the three sub-dimensions (Connectivity, Market, and GST) represented by stacked columns, together with the overall CMG index shown as a dashed line, for selected ASEAN countries in 2017 and 2022.

The results indicate substantial differences in the level of digital development among the analyzed countries. Singapore consistently achieved the highest CMG values in both years, reflecting its leading position across all three dimensions. High index values were also observed for Malaysia and Indonesia, which benefited from relatively strong performance in Connectivity and Market indicators.

A general upward trend can be observed between 2017 and 2022 for most countries, particularly in Lao P.D.R., Myanmar, Cambodia, and Vietnam. In these cases, the increase in the CMG index was primarily driven by improvements in the GST and Market dimensions, suggesting accelerated digital transformation and greater adoption of advanced digital technologies.

The Connectivity dimension appears relatively stable across the analyzed period, whereas larger changes are visible in the Market and GST components. This suggests that improvements in digital readiness were increasingly associated with the development of digital markets, technological capabilities, and supporting innovation ecosystems rather than with basic connectivity infrastructure alone.

Despite the overall positive trend, considerable disparities remain among countries. Singapore and Malaysia maintain a clear advantage over the less-developed economies of the region, while countries such as Cambodia, Lao P.D.R., and Myanmar, although showing notable progress, continue to record lower overall CMG values. These findings indicate ongoing convergence within the region, accompanied by persistent differences in the maturity of national digital ecosystems.

Table 3 presents descriptive statistics for the CMG index and its constituent dimensions (Connectivity, Market, and GST) across ASEAN countries in 2017 and 2022. The results indicate substantial heterogeneity in the level of digital transformation among the analyzed economies, although the degree of differentiation varied across dimensions and over time.

Table 3. Descriptive statistics for the CMG index and its sub-indexes in 2017 and 2022 separately.

		Min	Mean	Median	Sd	Max	Cv
Connectivity	2017	0.036	0.467	0.426	0.285	0.932	60.9%
	2022	0.138	0.557	0.559	0.276	0.970	49.6%
Market	2017	0.013	0.420	0.455	0.298	0.948	70.9%
	2022	0.010	0.310	0.291	0.177	0.628	57.0%
GST	2017	0.319	0.659	0.705	0.190	0.879	28.9%
	2022	0.480	0.684	0.633	0.165	1.000	24.2%
CMG	2017	0.123	0.515	0.570	0.213	0.758	41.3%
	2022	0.309	0.517	0.524	0.141	0.711	27.2%

Source: Authors' own analysis.

In 2017, the greatest disparities were observed in the Market dimension, for which the coefficient of variation reached 70.9%, indicating very high cross-country differentiation. A similarly high level of variability was recorded for Connectivity (60.9%), reflecting considerable differences in digital infrastructure and access among ASEAN member states. By contrast, the GST dimension exhibited significantly lower variability (28.9%), suggesting a more balanced distribution of this component across the region.

By 2022, the degree of differentiation decreased in all analysed dimensions. The coefficient of variation for Connectivity declined from 60.9% to 49.6%, while for Market it fell from 70.9% to 57.0%. The lowest variability was again observed for GST, with the coefficient of variation decreasing to 24.2%. These findings indicate a gradual convergence of ASEAN countries in terms of the analysed aspects of digital transformation, although substantial disparities remained, particularly in the market-related dimension.

Similar conclusions can be drawn from the synthetic CMG index. The coefficient of variation decreased from 41.3% in 2017 to 27.2% in 2022, indicating a notable reduction in the overall dispersion of digitalization levels among ASEAN countries. At the same time, the relatively high range between the minimum and maximum values confirms the continued existence of significant differences in digital development across the region.

Overall, the results support the conclusion that ASEAN countries differed considerably in their levels of digitalization, particularly in 2017. Although the observed decline in variability suggests a tendency toward convergence by 2022 (Table 4), the persistence of substantial disparities confirms that digital transformation across ASEAN remained uneven.

Therefore, the descriptive statistics provide empirical evidence supporting RH1, indicating that ASEAN member states exhibited substantial differences in their levels of digitalization, although these differences became less pronounced between 2017 and 2022.

Table 4. Cross-country disparities in CMG and its sub-indicators relative to the ASEAN average in 2017 and 2022.

Lowest-Highest Country Scores as a % of the ASEAN Average That Year		Included:		Difference [P.P.]	Degree of Recorded Differences	Assessing Changes in Implementing Convergence Processes
		Lowest Values [%]	Highest Values [%]			
Connectivity	2017	3.6	93.2	89.5	Degree 2	+
	2022	13.8	97.0	83.2		
Market	2017	1.3	94.8	93.5	Degree 3	+
	2022	1.0	62.9	61.8		
GST	2017	31.9	87.9	56.0	Degree 1	+
	2022	48.0	100.0	52.0		
CMG	2017	12.3	75.8	63.6		+
	2022	30.9	71.1	40.1		

Note 1: Lower differences between the highest and lowest country values indicate stronger convergence among ASEAN member states. **Note 2:** Degrees 1–3 classify the magnitude of the reduction in cross-country disparities between 2017 and 2022, where Degree 1 represents the smallest reduction and Degree 3 the largest. The symbol "+" denotes a narrowing of disparities (convergence), whereas "−" denotes a widening of disparities (divergence). A formal assessment of σ-convergence based on changes in the coefficient of variation is presented in Sections 3.3.8 and 4.6. Source: Authors' own analysis.

4.2. Robustness of the Index to the Weighting Scheme

To assess the impact of area-specific weights (i.e., the question of why each dimension was assigned an equal weight of one-third), the CMG index was recalculated using three alternative weighting schemes (Tables 5 and 6):

- equal weights (one-third assigned to each dimension; Equation (1)),
- weights derived from Principal Component Analysis (PCA; Equation (8)), and
- weights based on Shannon entropy (Equation (9)).

Table 5. Area-specific weights according to three weighting schemes (2017 and 2022).

Scheme for 2017	Connectivity	Market	GST
Equal weights	0.33	0.33	0.33
PCA	0.38	0.23	0.39
Shannon entropy	0.38	0.54	0.08
Scheme for 2022	**Connectivity**	**Market**	**GST**
Equal weights	0.33	0.33	0.33
PCA	0.31	0.38	0.31
Shannon entropy	0.38	0.54	0.08

Source: Authors' own analysis.

The resulting country rankings were subsequently compared.

The maximum change in a country's ranking position across all weighting schemes was two places in both 2017 and 2022, while the average change amounted to 1.0 and 0.6 positions, respectively. The country rankings proved highly robust to the choice of weighting scheme, with all Spearman rank correlation coefficients ranging from 0.903 to 0.988. No country changed its ranking position by more than two places under any weighting scenario. Therefore, the ordering of economies cannot be regarded as an artefact of the adopted weighting procedure.

Table 6. Ranking consistency (Spearman rank correlation) and position stability.

Measure	Equal-PCA	Equal-Entropy	PCA-Entropy
Spearman ρ, 2017	0.976	0.952	0.903
Spearman ρ, 2022	0.988	0.964	0.952

Source: Authors' own analysis.

The Shannon entropy weights substantially reduced the importance of the GST dimension (to approximately 0.08), reflecting its relatively low level of variation across countries. Despite this considerable change in weights, the resulting rankings remained highly stable. These findings indicate that the CMG index is robust to alternative weighting schemes, thereby supporting the reliability of the obtained country rankings and the validity of the comparative assessment of digital transformation across ASEAN economies.

4.3. Comparative Assessment of CMG Against Existing Indices

Table 1 presents a comparative assessment of the CMG index and selected international digitalization indices. The comparison indicates that all analysed indices address the multidimensional nature of digital development; however, they differ in their conceptual focus, methodological assumptions, and analytical objectives.

Unlike IDI, DAI, EGDI and ADII, the proposed CMG index explicitly separates infrastructure, digital market development and governance-related dimensions, allowing both comparative ranking and taxonomic profiling of countries. Consequently, CMG complements existing measures by providing a more detailed structural perspective on digital transformation.

4.4. Internal Consistency of the CMG Index

The internal consistency of the index was assessed by examining the linear correlations among the sub-indicators using Pearson's correlation coefficient (Equation (16)), as well as the correlations between each sub-indicator and the CMG index. In addition, Cronbach's alpha coefficient was calculated for the three sub-indicators (Table 7).

Table 7. Correlations among sub-indicators, correlations with the CMG index, and Cronbach's alpha.

Year	Connectivity-Market	Connectivity—GST	Market—GST	Cronbach's α
2017	0.414	0.761	0.434	0.743
2022	−0.004	0.567	−0.136	0.366

Source: Authors' own analysis.

In 2017, the internal consistency of the index was satisfactory (α = 0.743), given the fact that the index consists of three components, and all three sub-indicators exhibited strong correlations with the CMG index (Connectivity = 0.866, Market = 0.780, and GST = 0.840). In contrast, internal consistency declined markedly in 2022 (α = 0.366). The Market dimension was virtually uncorrelated with Connectivity (−0.004) and negatively correlated with GST (−0.136). These findings suggest that, by 2022, the Market dimension had become increasingly detached from the other dimensions of digital transformation, indicating that the components of the CMG framework no longer evolved in a fully complementary manner.

A possible explanation is that the growing importance of government regulations and administrative interventions, reflected in the GST dimension, may be associated with constraints on market freedom and entrepreneurial dynamics, thereby weakening the relationship between governance and market development. At the same time, once a relatively high level of Connectivity had been achieved, further improvements in digital infrastructure may have generated diminishing effects on market-related outcomes. Consequently, the negative GST–Market relationship and the near-zero Connectivity–Market correlation may reflect increasing structural differentiation among the dimensions of digital transformation rather than a measurement artifact.

Therefore, while the aggregated CMG index remains useful for comparative analyses, the 2022 results may suggest that greater emphasis should be placed on the individual dimensions of Connectivity, Market, and GST, as they capture distinct and potentially divergent development trajectories.

4.5. Cluster Analysis and Differences Between Groups

With reference to the research methodology, hierarchical cluster analysis using Ward's method was employed to assess the similarities in the level of digitalization among ASEAN countries. The choice of this taxonomic approach was motivated by its ability to identify relatively homogeneous groups of countries based on selected indicators. The clustering procedure involved:

- Grouping countries into clusters characterized by a high degree of similarity with respect to the analysed variables;
- Minimizing the within-cluster variance at each stage of the agglomeration process;
- Maximizing the differences between clusters while maintaining internal homogeneity of the groups;
- Identifying the hierarchical structure of similarities among countries through the agglomerative clustering process represented by a dendrogram.

4.5.1. Number of Clusters

Hierarchical agglomerative cluster analysis based on Ward's method and squared Euclidean distance (Equations (10) and (11)) was conducted for the C, M, and GST sub-indicators in 2017 and 2022 separately. For cluster solutions ranging from $k = 2$ to $k = 5$, cluster validity was assessed using the average silhouette coefficient (Equation (12)) and the Calinski–Harabasz index (Equation (13)).

For 2017, the three-cluster solution appears to be well justified (see Table 8). The Calinski–Harabasz index reached a value of 11.78 for (k = 3), which was close to its maximum, while the silhouette coefficient remained relatively high (0.410). Moreover, the agglomeration schedule revealed a pronounced increase in the linkage distance during the final stages of the clustering process (from 0.855 to 1.458), indicating the presence of several compact and well-separated groups.

In contrast, the clustering structure observed in 2022 was considerably weaker (Table 8). The silhouette coefficient for the three-cluster solution was only 0.284, while the selected validation criteria suggested that solutions with either (k = 2) or (k = 4) clusters might provide a better representation of the data structure. Nevertheless, the three-cluster solution was retained for 2022 in order to ensure comparability with the 2017 results, although its limited cluster separability should be explicitly acknowledged.

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Table 8. The number of clusters validation indexes.

2017		
k (number of clusters)	**Mean of silhouette coefficient**	**Calinski-Harabasz index**
2	0.462	10.77
3	0.410	11.78
4	0.390	11.95
5	0.370	11.50
2022		
k (number of clusters)	**Mean of silhouette coefficient**	**Calinski-Harabasz index**
2	0.287	6.59
3	0.284	6.15
4	0.308	6.87
5	0.276	6.87

Source: Authors' own analysis.

4.5.2. Result of Clustering Methods

The results of the clustering procedure for two selected years are presented in Figures 3 and 4.

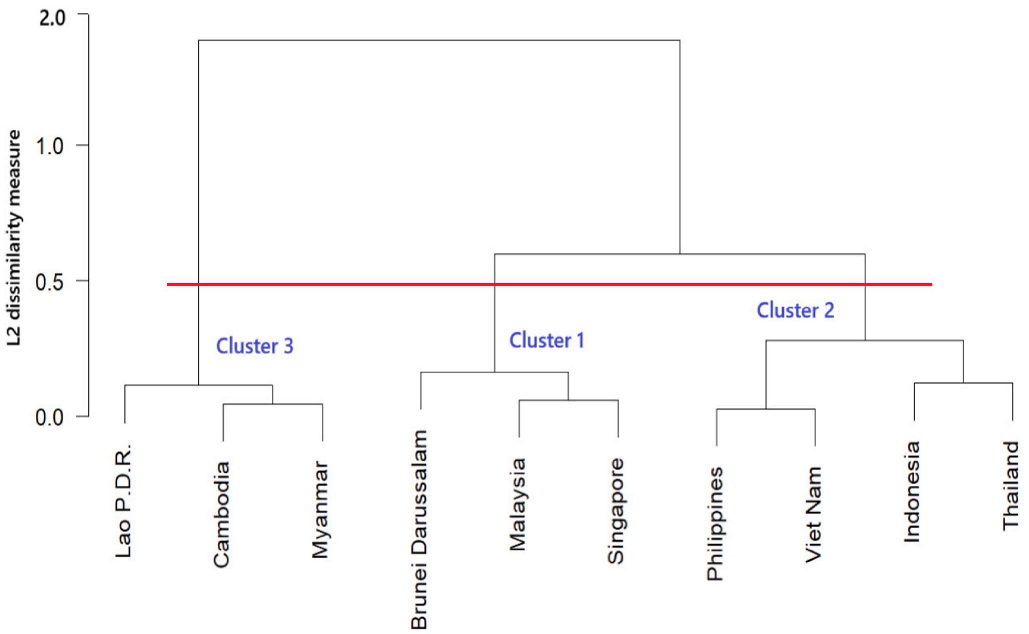

Figure 3. Dendrogram for the ASEAN countries based on sub-indicators of CMG in 2017. Source: Authors' own analysis.

The hierarchical clustering analysis, shown in Figure 3, represents the degree of the CMG sub-indicators, measuring the global development of ICTs at the level of access, uses, and skills in various ASEAN countries in 2017.

Based on Ward's method with squared Euclidean distances, the clustering of countries was provided with a priori cluster structures based on CMG sub-indicators. The dendrogram clearly identified three clusters. Cluster 1, consisting of Brunei Darussalam, Malaysia, and Singapore, shows a relatively higher similarity, probably because of advanced ICT development and similar policies. Cluster 2, consisting of Indonesia, the Philippines, Thailand, and Vietnam with moderate similarity and is at different levels of ICT development. Cluster 3, composed of Cambodia, Lao P.D.R., and Myanmar, formed a lower independent group probably due to their relatively lower ICT development and different socio-economic factors. Consequently, the clustering shows the different extents of socio-economic development and competitiveness among ASEAN countries in the year 2017.

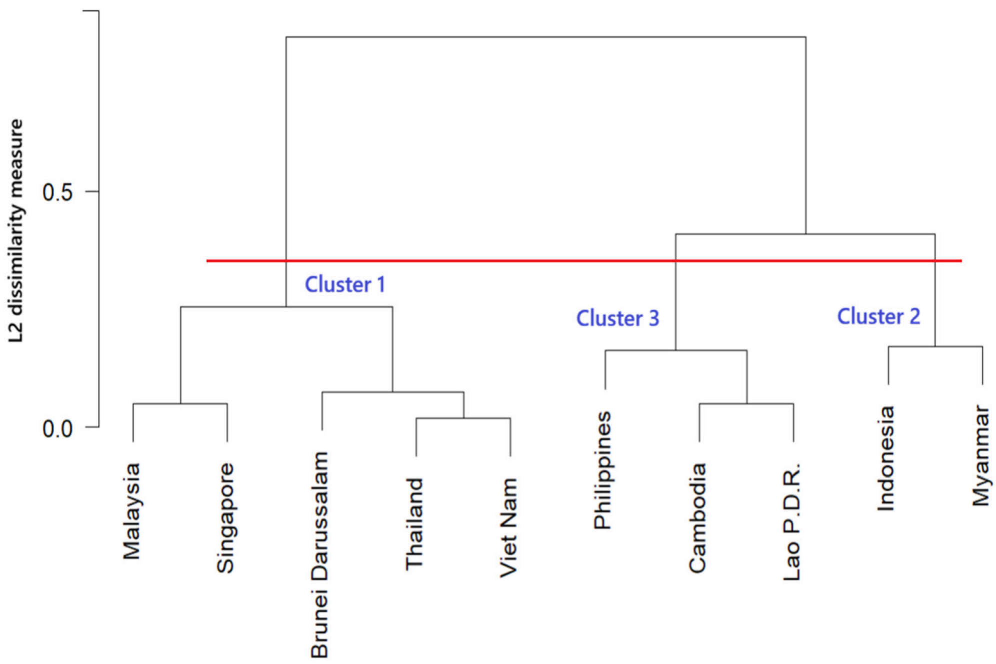

Figure 4. Dendrogram for the ASEAN countries based on sub-indicators of CMG in 2022. Source: Authors' own analysis.

The hierarchical clustering in Figure 4 for the year 2022 indicates the level of ICT development in ASEAN countries. Applying Ward's method using squared Euclidean distances for the countries under study, three distinct clusters are shown. Cluster 1 represents the countries Brunei Darussalam, Malaysia, Singapore, Thailand, and Vietnam, with high similarity probably due to their ICT development and similar policies. Cluster 2 consists of Indonesia and Myanmar with moderate similarity and a balance of ITC characteristics. Cluster 3 represents the countries Cambodia, Lao P.D.R., and the Philippines, characterized by a relatively low level of ICT development and weaker performance across the analysed indicators compared to the other clusters.

Therefore, this clustering enables us to make inferences concerning the relative ICT development and competitiveness levels among these countries in the year 2022. In Table 7 and Figure 5, the means of CMG and sub-indicators were presented.

The cluster analysis revealed significant differences in the level and structure of digital development among the identified groups (see Table 7 and Figure 5). In 2017, Group 1 achieved the highest average CMG value (0.687), driven by strong Connectivity and GST dimensions, while Group 3 exhibited the lowest performance across all indicators. In 2022, Group 1 maintained the highest CMG level (0.608), although its average value declined. Group 3 improved considerably, particularly in the Market dimension, resulting in a higher CMG value (0.485) than Group 2 (0.387). These results indicate a partial convergence of digital development levels among the analyzed clusters between 2017 and 2022.

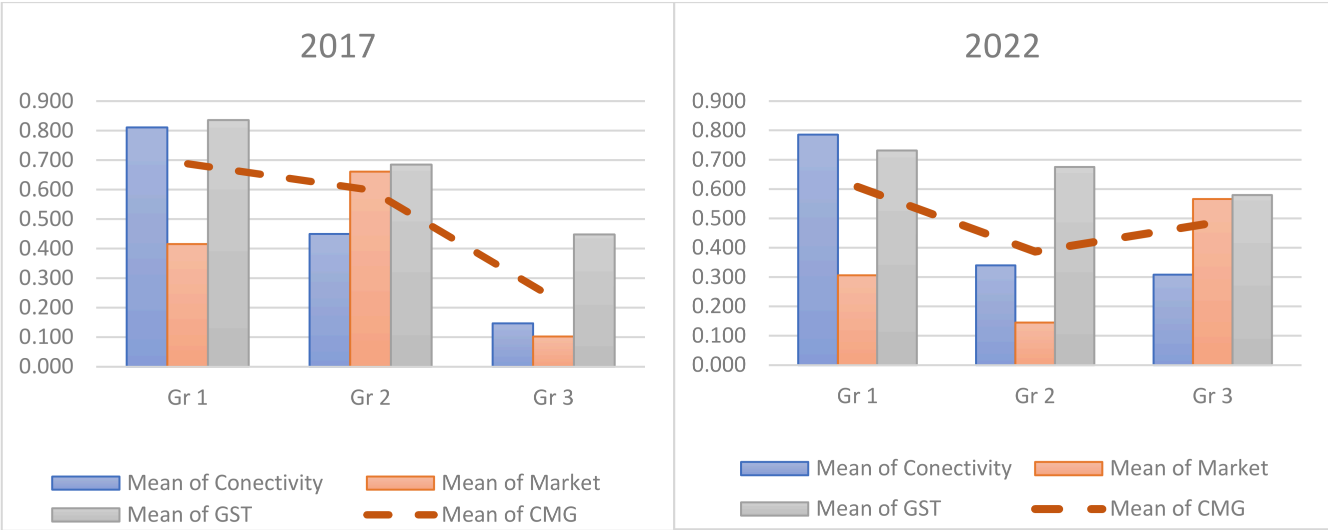

Figure 5. Comparative cluster means of values of the CMG and its sub-components in ASEAN countries in 2017 and 2022. Source: Authors' own analysis.

4.5.3. Dynamics of Digital Transformation Across Clusters

The dynamics of digital transformation among ASEAN countries in 2017 and 2022 are presented in the table below (Figure 6), together with the changes in the values of CMG and its sub-indicators.

	Cluster 1	Cluster 2	Cluster 3
In 2017	Brunei Darussalam Singapore Malaysia	Indonesia Philippines Thailand Viet Nam	Cambodia Laos P.D.R. Myanmar
Mean of CMG	0.687	0.599	0.232
Mean of Connectivity	0.811	0.450	0.147
Mean of Market	0.416	0.661	0.102
Mean of GST	0.836	0.685	0.448
In 2022	Malaysia Singapore Brunei Darussalam Thailand Viet Nam	Indonesia Myanmar	Cambodia Laos P.D.R. Philippines
Mean of CMG	0.608	0.387	0.485
Mean of Connectivity	0.786	0.340	0308
Mean of Market	0.306	0.145	0.566
Mean of GST	0731	0.676	0.580

Figure 6. Value of the CMG indicator and its sub-components in a cross-section of isolated clusters for ASEAN countries in 2017 and 2022. (The colour coding identifies groups of countries according to their cluster membership in 2017. The same colour is assigned to countries originating from the same cluster, irrespective of their cluster membership in 2022. Arrows indicate the direction of changes in cluster assignment between 2017 and 2022. Source: Authors' own analysis.

Additionally, the hierarchical clustering results for 2017 and 2022 indicate notable changes in the ICT development landscape of ASEAN countries. While three distinct clusters were identified in both years, the differences between clusters became less pronounced in 2022. This is reflected in the reduced dispersion of average CMG values across groups, suggesting a partial convergence in digital development levels. The most significant improvement was observed in Cluster 3, whose average CMG value increased from 0.232 to 0.485 (Figure 6), indicating a catching-up process among less digitally developed economies. In contrast, Clusters 1 and 2 experienced declines in their average CMG values, although Cluster 1 remained the most advanced group. These findings may reflect differences in national digital transformation trajectories and suggest that progress in digital development is increasingly driven by qualitative improvements rather than basic infrastructure expansion alone.

Particularly noteworthy are the transitions of the Philippines and Myanmar between clusters. The Philippines moved from Cluster 2 to Cluster 3, suggesting a stronger market-oriented pattern of digital development despite persistent challenges in connectivity and governance dimensions. In contrast, Myanmar shifted from Cluster 3 to Cluster 2, reflecting a relatively weaker market dimension and a development trajectory more strongly associated with governance-related factors.

4.5.4. Significance of Differences Between Groups

Differences in CMG values across the identified clusters were assessed using the non-parametric Kruskal–Wallis test (Equation (15)), which is particularly appropriate for small samples and does not require the assumptions of normality or homogeneity of variances (Table 9).

Table 9. Kruskal–Wallis Test Results for Differences in CMG Across Clusters.

Year	Kruskal–Wallis H (p)	Result (α = 0.05)
2017	6.745 (p = 0.0343)	Significant differences
2022	5.251 (p = 0.0724)	Differences at the borderline of significance

Source: Authors' own analysis.

In 2017, the Kruskal–Wallis test revealed statistically significant differences in CMG values among the identified clusters (H = 6.745, p = 0.0343). This result indicates that the clusters represented distinct levels of digitalization and confirms the existence of substantial disparities among groups of ASEAN countries. Consequently, the findings provide empirical support for RH2. In contrast, the results for 2022 were weaker. Although the Kruskal–Wallis statistic remained relatively high (H = 5.251), the corresponding p-value (p = 0.0724) exceeded the conventional significance threshold of 0.05. Therefore, the null hypothesis of equal distributions across clusters cannot be formally rejected. Nevertheless, the result may be interpreted as indicating a tendency toward differentiation among clusters, albeit with weaker statistical support than in 2017.

The observed decline in statistical significance between 2017 and 2022 is consistent with the reduction in the dispersion of CMG values across ASEAN countries and suggests a gradual convergence in digital transformation levels within the region. Overall, RH2 is strongly supported for 2017, whereas for 2022 the evidence points to only partial support, reflecting the persistence of cluster differences alongside a reduced degree of separation between them.

The country-level analysis of the CMG indicator has outlined several changes between the two surveyed years. These changes are positive and show an increase in the CMG development. In the analyzed years, three of the ten ASEAN countries had below-average, while seven countries were above average in the ASEAN. Countries below the average, both in 2017 and 2022, were Cambodia, Lao PDR, and Myanmar. In 2017, the lowest country-level CMG score was by Lao PDR, with 0.1225 points, while in 2022, it was also Lao PDR, with a slight increase to 0.3093 points. Countries with above-average CMG values in both years included Brunei Darussalam, Indonesia, Malaysia, the Philippines, Thailand, Vietnam, and Singapore. Comparing the performance of individual countries against the ASEAN average in 2017, it was found that Lao PDR had the lowest rate of 23.7%, while Singapore had the highest rate of 147%. Similarly, in 2022, it was found that Lao PDR had the lowest rate of 60.1%, while Singapore had the highest 137.9% rate.

The fact that the gap between the lowest and highest rates, as compared to the ASEAN average, has been gradually decreasing from 63.6 pps in 2017 to 40.1 pps in 2022, gives a positive trend toward more convergence across ASEAN countries. This positive trend is further diluted by the countries' observation, where the value of the ratio between the highest and the lowest rates dropped from 6.2 in 2017 to a far lower value of 2.2 in 2022.

4.6. Sigma Convergence as a Measure of Disparity Reduction

To evaluate whether disparities in digital development decreased over time, σ-convergence was examined using the coefficient of variation (V) calculated for the CMG index and its constituent sub-indices in 2017 and 2022 (Table 10).

Table 10. Coefficient of Variation (V) in 2017 and 2022: Evidence of σ-Convergence.

Index	*V* 2017	*V* 2022	Δ*V*	Trend
CMG	0.413	0.272	−0.141	Convergence
Connectivity	0.609	0.496	−0.114	Convergence
Market	0.709	0.570	−0.139	Convergence
GST	0.289	0.242	−0.047	Convergence

Source: Authors' own analysis.

The results presented in the above table provide evidence of σ-convergence in digital development among ASEAN countries between 2017 and 2022. The coefficient of variation decreased for the composite CMG index as well as for all three sub-indices, indicating a reduction in disparities across countries.

The strongest convergence was observed for the CMG index (ΔV = −0.141), suggesting a substantial decline in overall differences in digital development levels. Similar patterns were recorded for the Market dimension (ΔV = −0.139) and Connectivity (ΔV = −0.114), indicating that countries became more similar in terms of digital infrastructure and market development. Although the GST dimension also exhibited convergence, the reduction in dispersion was less pronounced (ΔV = −0.047), suggesting that differences in governance, adoption, skills, and technological readiness remained relatively more persistent.

Overall, the findings indicate that less digitally advanced countries have been gradually catching up with regional leaders, leading to a more balanced distribution of digital development across ASEAN economies.

4.7. Analysis of Dynamic Indexes in Clusters

Table 11 reveals substantial differences in the dynamics of digital development across the identified clusters between 2017 and 2022. Cluster 3 recorded by far the strongest growth, with the CMG index increasing to 209.05% of its 2017 level. Particularly remarkable growth was observed in the Market dimension (554.90%) and Connectivity (209.52%), indicating a rapid digital catching-up process among the least developed economies. The GST dimension also improved considerably, reaching 129.46% of its initial value.

Table 11. Dynamics of CMG and its sub-indicators across clusters, 2017–2022 (2017 baseline = 100%).

Cluster Number	Connectivity	Market	GST	CMG
1	96.92%	73.56%	87.44%	88.50%
2	75.56%	21.94%	98.69%	64.61%
3	209.52%	554.90%	129.46%	209.05%
Average ASEAN	127.33%	216.80%	105.20%	120.72%

Source: Authors' own analysis.

In contrast, Clusters 1 and 2 experienced declines in most dimensions (Table 11). Cluster 1 maintained a relatively high level of digital development, but its CMG index decreased to 88.50% of the 2017 level, suggesting a slowdown in growth among the regional leaders. Cluster 2 recorded the weakest performance, with a substantial decline in both the CMG index (64.61%) and the Market dimension (21.94%), indicating a loss of momentum in digital transformation.

At the ASEAN level, the CMG index increased by 20.72%, reflecting overall progress in digital development across the region. However, the aggregate results conceal considerable heterogeneity among clusters. The strong improvements observed in Cluster 3 were partly offset by weaker performance in Clusters 1 and 2. These findings support the existence of a digital convergence process within ASEAN, driven primarily by rapid advances among less digitally developed countries.

4.8. Relationship Between Digitalization and the Level of Economic Development

The relationship between the CMG index and the level of economic development was examined using Pearson's correlation coefficient (Equation (16)), Spearman's rank correlation coefficient (Equation (17)), and a linear regression model relating CMG to the natural logarithm of GDP per capita (Equation (18)). Data on GDP per capita (current US dollars) were obtained from the World Bank's World Development Indicators database (indicator: NY.GDP.PCAP.CD).

The results reveal a positive and statistically significant relationship between the level of digitalization and economic development across ASEAN countries. In both analysed years, Pearson's correlation coefficients indicate a moderately strong positive linear association between CMG and the logarithm of GDP per capita, amounting to 0.686 ($p = 0.0285$) in 2017 and 0.763 ($p = 0.0103$) in 2022. The stronger correlation observed in 2022 suggests that the link between digital transformation and economic prosperity intensified over the analysed period.

The rank-based analysis produced even stronger results. Spearman's correlation coefficient reached 0.818 ($p = 0.0038$) in both years, indicating a highly consistent monotonic relationship between the level of digitalization and countries' relative economic positions. This finding suggests that more economically developed ASEAN countries systematically achieved higher CMG scores than less developed economies.

The regression analysis (see Table 12) further confirms this relationship. In 2017, the estimated regression coefficient amounted to $\beta_1 = 0.1135$ ($p = 0.0285$), while in 2022 it reached $\beta_1 = 0.0792$ ($p = 0.0103$). The explanatory power of the model increased over time, with the coefficient of determination rising from $R^2 = 0.470$ in 2017 to $R^2 = 0.582$ in 2022. Consequently, approximately 58% of the variation in the CMG index observed in 2022 can be explained by differences in GDP per capita among ASEAN countries.

Table 12. Relationship between CMG and GDP per Capita: correlation and regression results.

Year	Pearson's (r) CMG—ln(PKB *)	Spearman's (ρ) CMG—PKB *	Regression: β_1 (p), R^2
2017	0.686 (p = 0.0285)	0.818 (p = 0.0038)	0.1135 (p = 0.0285); R^2 = 0.47
2022	0.763 (p = 0.0103)	0.818 (p = 0.0038)	0.0792 (p = 0.0103); R^2 = 0.582

* Values PKB per capita in current US dollars from the World Bank's World Development Indicators. Source: Authors' own analysis.

Overall, the empirical evidence strongly supports RH3. Countries characterized by higher levels of economic development tend to exhibit higher levels of digitalization, confirming the existence of a robust positive association between the CMG index and GDP per capita across ASEAN economies.

Contextual Background of the ASEAN Economies

To enhance the contextual interpretation of the results, it is important to consider the broader structural and macroeconomic characteristics of ASEAN economies. In 2022, the region exhibited a relatively diversified economic structure, with manufacturing accounting for 21.2% of total GDP, followed by trade (14.7%) and public administration and other services (10.3%). At the same time, selected sectors—particularly accommodation and transportation—recorded exceptionally high growth rates (23.8% and 16.0%, respectively), reflecting post-pandemic recovery dynamics and the gradual normalization of economic activity [51].

However, the sectoral composition varies significantly across ASEAN countries, indicating substantial structural heterogeneity that may influence the observed clustering patterns. While manufacturing plays a dominant role in economies such as Thailand, Vietnam, and Malaysia, other countries remain more dependent on primary sectors (e.g., agriculture in Cambodia and Lao PDR) or extractive industries (e.g., mining in Brunei). These differences suggest that the level of digitalization captured by the index is likely intertwined with the stage of economic development and production structure [51].

Furthermore, the rapid expansion of the digital economy constitutes an important contextual factor shaping cross-country differences. By 2022, ASEAN had approximately 460 million internet users, with a significant share of new users emerging in the post-2019 period. This dynamic growth, supported by expanding ICT infrastructure and a digitally active population, has accelerated digital transformation processes across the region [37]. At the same time, substantial disparities persist in terms of internet penetration, digital skills, and technological capabilities, reflecting a multidimensional digital divide between high-income and lower-income economies [52,56].

Taken together, these contextual factors—namely sectoral structure, level of economic development, and digital infrastructure—provide an important background for interpreting the empirical results. They suggest that the identified patterns are not solely driven by the constructed index but also reflect broader structural differences across ASEAN countries, thereby strengthening the robustness and interpretability of the findings [10–12,51].

Although the analysis is limited to data up to 2022, recent evidence for 2023–2025 indicates a continued post-pandemic recovery and sustained growth momentum in digitally intensive sectors, confirming the increasing role of digital transformation in ASEAN economies [87,88].

5. Discussion

The discussion of cluster-specific results refers to the hierarchical clustering obtained separately for each study year. Consequently, cluster memberships differ between 2017 and 2022, reflecting changes in the relative similarity of ASEAN countries in terms of the CMG sub-indicators.

5.1. Connectivity

The Connectivity dimension showed the strongest improvement among the three CMG components between 2017 and 2022. Although considerable disparities remain across ASEAN member states, the results indicate a gradual reduction in relative differences, particularly due to rapid improvements in countries with initially lower levels of digital infrastructure. At the same time, the persistence of substantial absolute gaps confirms that infrastructure expansion alone is insufficient to achieve balanced digital transformation.

These findings are consistent with international evidence indicating that broadband infrastructure and internet access constitute the primary drivers of digital convergence in developing economies. Previous studies and reports by the ITU and the World Bank identify connectivity as the fastest-growing dimension of digital transformation and a necessary prerequisite for wider digital participation [89,90]. However, the literature also emphasizes that the digital divide increasingly extends beyond physical access to encompass differences in affordability, service quality, digital skills, and effective use of digital technologies [6].

The cluster analysis supports this interpretation. Countries belonging to the least digitally developed cluster experienced the fastest improvements, reflecting a typical catch-up process based on infrastructure expansion. In contrast, more digitally advanced economies recorded slower growth, suggesting that future progress increasingly depends on improving the quality, resilience, and inclusiveness of digital infrastructure rather than further expanding access. These findings illustrate the analytical value of the CMG framework by demonstrating that improvements in connectivity do not necessarily translate into comparable progress in other dimensions of digital transformation, particularly market development and governance. Consequently, connectivity should be regarded as a necessary, but not sufficient, condition for long-term digital convergence within ASEAN [91].

5.2. Market

Unlike Connectivity, the Market dimension exhibited a less uniform development pattern. Although relative disparities between countries narrowed over time, the overall decline observed in several economies suggests that digital market development remains more sensitive to institutional, regulatory, and external economic conditions than infrastructure deployment. Positive dynamics were concentrated in only a small number of catching-up economies, indicating that market development follows heterogeneous rather than linear trajectories.

This interpretation is consistent with previous studies highlighting persistent structural barriers to ASEAN market integration. Regulatory fragmentation, non-tariff measures, and differences in national institutional frameworks continue to limit the development of integrated digital markets, particularly for small and medium-sized enterprises [92]. Moreover, foreign direct investment remains unevenly distributed across the region, concentrating digital business opportunities in a limited number of economies and reinforcing structural asymmetries [93].

External shocks further contributed to these developments. The weakening of international trade, geopolitical uncertainty, and the reorganization of global supply chains toward the end of the analyzed period created additional constraints on digital market expansion and regional integration [94]. Consequently, the observed decline in Market scores should not be interpreted solely as weaker digital performance but rather as reflecting the combined effects of institutional fragmentation, uneven investment patterns, and increasing external uncertainty. The CMG framework captures these differences by distinguishing market-related dynamics from infrastructure and governance, thereby revealing structural heterogeneity that remains less visible in conventional composite indices [95].

5.3. Governance, Sustainability and Trust (GST)

The GST dimension demonstrated gradual but uneven improvement across ASEAN countries. While several member states strengthened governance-related indicators during the study period, institutional convergence remained considerably slower than convergence in digital infrastructure. This suggests that governance-related aspects of digital transformation evolve incrementally and depend largely on long-term institutional capacity and regulatory maturity.

These findings are consistent with ASEAN's ongoing efforts to improve regulatory quality through initiatives promoting Good Regulatory Practice, Regulatory Management Systems, and enhanced regional cooperation [96]. National reforms undertaken before 2022, including regulatory modernization in Vietnam, Indonesia's Omnibus Law, and Singapore's continued digital government initiatives, are broadly consistent with the improvements observed in governance-related indicators. Nevertheless, implementation remains uneven across member states, reflecting differences in administrative capacity and the consensus-based institutional architecture of ASEAN.

The results highlight that governance, sustainability, and trust constitute complementary conditions for successful digital transformation rather than automatic outcomes of infrastructure expansion. The persistence of differences between country clusters indicates that long-term digital convergence depends not only on technological investment but also on the quality of institutions, regulatory coherence, and public trust. By explicitly incorporating these institutional dimensions, the CMG framework provides a broader perspective on digital transformation than infrastructure-oriented measures alone and helps explain why countries with similar connectivity levels may exhibit markedly different digital development trajectories.

6. Conclusions

This study addresses an important gap in the literature by proposing a transparent and replicable framework for assessing digital transformation across ASEAN economies. The CMG index, constructed from publicly available ITU indicators and organized into three complementary dimensions—Connectivity, Market, and Governance, Sustainability and Trust (GST)—provides a multidimensional perspective on digital development that extends beyond existing aggregate measures. Rather than focusing solely on overall levels of digitalization, the proposed framework enables the identification of structural differences in national digital transformation pathways.

The empirical findings confirm substantial heterogeneity in digital development across ASEAN countries. Although the overall level of digitalization increased during 2017–2022, progress differed considerably across countries and across the three dimensions of the CMG framework. Connectivity exhibited the strongest convergence, reflecting continued expansion of digital infrastructure, whereas the Market dimension revealed a more uneven development pattern influenced by regulatory, investment, and structural factors. Improvements in the GST dimension suggest gradual strengthening of governance and institutional conditions, although important differences among countries remain.

The study provides empirical support for all three research hypotheses. First, ASEAN member states continue to display significant cross-country differences in digitalization levels. Second, the cluster analysis identifies distinct groups of countries characterized by similar digitalization profiles, confirming persistent structural heterogeneity within the region. Third, digitalization is positively associated with broader indicators of economic and social development, although the results also demonstrate that relatively advanced digital performance may be achieved by countries with only moderate income levels, highlighting the multidimensional nature of digital transformation.

From a methodological perspective, the principal contribution of the study lies in the development of a composite indicator that combines conceptual transparency, straightforward replication, and structural analytical capability. Unlike aggregate measures that provide a single summary score, the CMG framework distinguishes infrastructure, market, and governance-related dimensions, thereby supporting more detailed comparative, taxonomic, and longitudinal analyses. The combination of the composite indicator with cluster analysis further demonstrates the usefulness of the framework for identifying different digital transformation trajectories across countries.

The findings also have important policy implications. The observed heterogeneity suggests that uniform digital policies are unlikely to produce balanced regional outcomes. More digitally advanced economies should increasingly prioritize regulatory innovation, cross-border interoperability, artificial intelligence, and data-driven ecosystems. Countries at intermediate stages of digital development would benefit from strengthening institutional quality and supporting digital entrepreneurship, while economies following catch-up trajectories should continue investing in digital infrastructure, expanding connectivity, and improving regulatory capacity. Such differentiated policy approaches are consistent with ASEAN's broader digital integration agenda.

The study has several limitations. First, the empirical analysis is limited to ASEAN member states and the period 2017–2022. Second, the CMG framework relies on indicators available in the ITU database and therefore does not fully capture emerging dimensions of digital transformation, including artificial intelligence adoption and platform economy development. Third, equal weighting was adopted to maximize transparency and comparability of the composite index, although alternative weighting schemes could be explored in future studies despite the robustness analysis indicating stable rankings.

Future research could extend the temporal coverage beyond 2022 to capture post-pandemic digital transformation and the growing importance of emerging technologies. Further studies may also incorporate sectoral and firm-level data, particularly regarding SMEs and industry-specific digitalization pathways, while comparative applications of the CMG framework to other regional organizations could provide additional evidence of its analytical usefulness and external validity.

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Abbreviations

The following abbreviations are used in this manuscript:

ADII	ASEAN Digital Integration Index
ASEAN	The Association of Southeast Asian Nations
The CMG Indicator	The measure enabling the hierarchy of economies according to the three areas: – Connectivity Area (*C*), – Markets Area (*M*), – Governance, Sustainability and Trust Area (*GST*).
DAI	Digital Adoption Index
EGDI	The E-Government Development Index
IDI	The ICT Development Index

References

1. Siuta Tokarska, B.; Juchniewicz, J.; Kowalik, M.; Thier, A.; Gross Gołacka, E. Family SMEs in Poland and their strategies: The multi criteria analysis in varied socio economic circumstances of their development in context of Industry 4.0. *Sustainability* **2023**, *15*, 14140. [CrossRef]
2. Götz, M. Przemysł czwartej generacji (przemysł 4.0) a międzynarodowa współpraca gospodarcza/ Industry 4.0 (the Fourth Industrial Revolution) and International Economic Cooperation. *Ekonomista* **2018**, *2018*, 385–403.
3. Aryani, Y.; Andari, W.; Suhindarto. Impact of information technology and e-commerce on Indonesia's trade with ASEAN countries. In *Harnessing Digitalization for Sustainable Economic Development: Insights for Asia*; Beirne, J., Fernandez, D.G., Eds.; Asian Development Bank Institute: Tokyo, Japan, 2022.
4. Gradillas, M.; Thomas, L.D.W. Distinguishing Digitization and Digitalization: A Systematic Review and Conceptual Framework. *J. Prod. Innov. Manag.* **2023**, *42*, 112–143. [CrossRef]
5. Horváth, D.; Szabó, R.Z. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *Technol. Forecast. Soc. Change* **2019**, *146*, 119–132. [CrossRef]
6. Vassilakopoulou, P.; Hustad, E. Bridging digital divides: A literature review and research agenda for information systems research. *Inf. Syst. Front.* **2023**, *25*, 955–969. [CrossRef] [PubMed]
7. Marsan, G.A. Addressing the Digital Divide in ASEAN. East Asia Forum Blog. 2022. Available online: https://www.eastasiaforum.org (accessed on 2 July 2026).
8. Ing, L.Y.; Rodrik, D. (Eds.) *New Normal, New Technologies, New Financing*; Economic Research Institute for ASEAN and East Asia: Jakarta, Indonesia; International Economic Association: Catalonia, Spain, 2022.
9. Klima, E. Państwo—Historia idei./The State: A History of an Idea. *Acta Univ. Lodziensis Folia Geogr. Socio-Econ.* **2009**, 3–20.
10. ASEAN. *Investing in ASEAN: One Vision, One Identity, One Community*; Allurentis: Haywards Heath, UK, 2023. Available online: https://asean.org/wp-content/uploads/2022/12/investment-report-2023.pdf (accessed on 2 July 2026).
11. ASEAN Indonesia. Digital Economy Framework Agreement (DEFA): ASEAN to Leap Forward its Digital Economy and Unlock US$2 Tn by 2030. ASEAN Indonesia, 2023. Available online: https://asean.org/asean-defa-study-projects-digital-economy-leap-to-us2tn-by-2030/ (accessed on 2 July 2026).
12. ASEAN Secretariat. *ASEAN Statistical Yearbook 2023*; ASEAN Secretariat: Jakarta, Indonesia, 2023.
13. Muhamad, S.; Kusairi, S.; Man, M.; Majid, N.F.H.; Wan Kassim, W.Z. Digital adoption by enterprises in Malaysian industrial sectors during the COVID-19 pandemic: A data article. *Data Brief* **2021**, *37*, 10719. [CrossRef] [PubMed]
14. Murphy, A. Understanding sustainable growth in Southeast Asia. In *ASEAN: Investing in ASEAN: One Vision, One Identity, One Community*; Allurentis: Haywards Heath, UK, 2023.
15. Srisathan, W.A.; Naruetharadhol, P. A COVID-19 disruption: The great acceleration of digitally planned and transformed behaviors in Thailand. *Technol. Soc.* **2022**, *68*, 101912. [CrossRef] [PubMed]

16. Tobing, D.H. Preparing Southeast Asia's Youth to Enter the Digital Economy. Asian Development Blog, 2022. Available online: https://blogs.adb.org/blog/preparing-southeast-asia-s-youth-enter-digital-economy (accessed on 2 July 2026).
17. Yu, M. The development of Southeast Asia's digital economy: Current status, development motivation and challenges. *Econ. Reg. Stud.* **2024**, *17*, 314–330. [CrossRef]
18. Li, L.; Dou, Y.; Cao, X.; Ding, W. The Impact of Digital Divide on the Level of High-Quality Economic Development: Evidence from China-ASEAN. *J. Knowl. Econ.* **2025**, *16*, 7235–7249. [CrossRef]
19. Bruno, G.; Diglio, A.; Piccolo, C.; Pipicelli, E. A reduced composite indicator for digital divide measurement at the regional level: An application to the Digital Economy and Society Index (DESI). *Technol. Forecast. Soc. Change* **2023**, *190*, 122461. [CrossRef]
20. Choczyńska, A.; Rani, S.; Tora, J. Comparison of international digitalisation indexes: A quantitative analysis perspective. *Int. Entrep. Rev.* **2024**, *10*, 25–42. [CrossRef]
21. Schilirò, D. *Digital Technologies for Entrepreneurship in Industry 4.0*; IGI Global: Hershey, PA, USA, 2022.
22. UNCTAD. *Digital Economy Report 2021: Cross-Border Data Flows and Development*; UNCTAD: Geneva, Switzerland, 2021.
23. Bauer, M.; Ferracane, M.; van der Marel, E. Tracing the Economic Impact of Regulations on the Free Flow of Data and Data Localization. Paper Series no 30, CIGI, Chatham House, The Royal Institute of International Affairs, Ontario-London 2016, 1–19. Available online: https://www.cigionline.org/static/documents/gcig_no30web_2.pdf (accessed on 2 July 2026).
24. Panetto, H.; Iung, B.; Ivanov, D.; Weichhart, G.; Wang, X. Challenges for the cyber-physical manufacturing enterprises of the future. *Annu. Rev. Control* **2019**, *47*, 200–213. [CrossRef]
25. Xu, L.D.; Xu, E.L.; Li, L. Industry 4.0: State of the Art and Future Trends. *Int. J. Prod. Res.* **2018**, *56*, 2941–2962. [CrossRef]
26. Ruchika, B. *Cybersecurity and Cyberwar: What Everyone Needs to Know*; Lap Lambert Academic Publishing: London, UK, 2024.
27. OECD. *Broadband Policy and Technology Developments*; OECD Digital Economy Papers; OECD Publishing: Paris, France, 2021.
28. Stock, T.; Seliger, G. Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP* **2016**, *40*, 536–541. [CrossRef]
29. Kovač, N.; Żmija, K.; Roy, J.K.; Kusa, R.; Duda, J. Digital divide and digitalization in Europe: A bibliometric analysis. *Equilibrium. Q. J. Econ. Econ. Policy* **2024**, *19*, 463–520. [CrossRef]
30. Siuta Tokarska, B.; Żmija, K.; Kruk, S.; Krzemiński, P.; Thier, A. *Digital Transformation of Small and Medium Sized Enterprises in the Visegrad Countries: Developmental Similarities and Differences*; PTE: Warsaw, Poland, 2025.
31. Asian Development Bank. *Capturing the Digital Economy: A Proposed Measurement Framework and Its Applications (A Special Supplement to Key Indicators for Asia and the Pacific 2021*; Asian Development Bank: Manila, Philippines, 2021.
32. Kraus, S.; Durst, S.; Ferreira, J.J.; Veiga, P.; Kailer, N.; Weinmann, A. Digital transformation in business and management research: An overview of the current status quo. *Int. J. Inf. Manag.* **2022**, *63*, 102466. [CrossRef]
33. Verhoef, P.C.; Broekhuizen, T.; Bart, Y.; Bhattacharya, A.; Dong, J.Q.; Fabian, N.; Haenlein, M. Digital transformation: A multidisciplinary reflection and research agenda. *J. Bus. Res.* **2021**, *122*, 889–901. [CrossRef]
34. Hanelt, A.; Bohnsack, R.; Marz, D.; Marante, C.A. A Systematic Review of the Literature on Digital Transformation: Insights and Implications for Strategy and Organizational Change. *J. Manag. Stud.* **2021**, *58*, 5. [CrossRef]
35. Jiang, Q.; Tu, Y.; Tu, J. Digital Transformation and Technological Innovation in Emerging Economies: Substitution Effects and Regional Heterogeneity in China's Foreign Trade. *Economies* **2026**, *14*, 126. [CrossRef]
36. Xiao, D.; Zhang, C.; Huang, Y. Digital Economy Policy and Enterprise Digital Transformation: Evidence from Innovation and Structural Effect. *Manag. Decis. Econ.* **2024**, *45*, 2348–2359. [CrossRef]
37. Suranto, B.; Kovač, N.; Haryono, K.; Rahman, S.F.A.; Shukri, A.F.M.; Suder, M.; Kusa, R.; Žugić, D. State of digitalization in the Southeast Asia region—Bibliometric analysis. *Qual. Quant.* **2026**, *60*, 1053–1080. [CrossRef]
38. Aumeboonsuke, V. Digital Convergence and Divergence in EU and ASEAN Economies. *Econ. Innov. Econ. Res. J.* **2025**, *13*, 153–177.
39. Hutchinson, L.; Ahmad, W. The Digital Divide: A Global Perspective on Inequality and Exclusion. *Sci. Acad.* **2024**, *5*, 108–111.
40. Zhang, L.; Pham, T.D.; Li, R.; Do, T.T. Enhancing the Sustainable Development of the ASEAN's Digital Trade: The Impact Mechanism of Innovation Capability. *Sustainability* **2025**, *17*, 1766. [CrossRef]
41. Isono, I.; Prilliadi, H. *ASEAN's Digital Integration: Evolution of Framework Document*; Economic Research Institute for ASEAN and East Asia (ERIA): Jakarta, Indonesia, 2023.
42. Lee, J.O. How ASEAN Is Building Trust in Its Digital Economy. WEF Agenda, 12 January 2024. Available online: https://www.weforum.org/agenda/2024/01/asean-building-trust-digital-economy/ (accessed on 2 July 2026).
43. Ing, E.Y. (Ed.) *ASEAN Digital Community 2045 Country Perspectives*; ERIA Research Project Report FY2025 No. 14; Economic Research Institute for ASEAN and East Asia (ERIA): Jakarta, Indonesia, 2026.
44. ITU. *Digital Policy Action Areas for a Connected ASEAN. ASEAN Best Practice Benchmarking and an Action Plan for Regional Harmonization*; ICT: Geneva, Switzerland, 2024.
45. The ASEAN Secretariat. *Enhancing Connectivity and Resilience*; Annual Report 2024; The ASEAN Secretariat: Jakarta, Indonesia, 2024.

46. Weno, R.; Suhartono, H.; Heryanto, T.; Kiantara, R.; Adinda, C.; Putra, A. Artificial Intelligence (AI) and Digital Transformation in the ASEAN Region. In *Can ASEAN Govern the Rise of AI? Power, Risk, Opportunity, 2025*; ASEAN: South Jakarta, Indonesia, 2025. Available online: https://asean-bac.org/news-and-press-releases/artificial-intelligence-(ai)-and-digital-transformation-in-the-asean-region (accessed on 2 July 2026).
47. Chakravorti, B.; Chaturvedi, R.S.; Filipovic, C.H.; Niu, X. *Digital Planet 2025. From the COVID Shock to the AI Surge: How 125 Digital Economies Around the World Are Evolving and Changing*; Institute for Business in the Global Context; The Fletcher School at Tufts University: Medford, MA, USA, 2025.
48. Singh, S.K. The Digital Divide: Review and Policymaking in the Asian Context. In *Harnessing Digital Transformation for Good: Asian Development Policy Report 2025*; The Asian Development Bank: Mandaluyong City, Philippines, 2025.
49. Atobishi, T.; Mansur, H. Bridging Digital Divides: Validating Government ICT Investments Accelerating Sustainable Development Goals. *Sustainability* **2025**, *17*, 2191. [CrossRef]
50. Rashid, A.A.; Hanif, A.; Mohamad Shukri, N.H.; Žugić, D. Bridging the digital divide in ASEAN: Insights from Vietnam, Philippines, Laos, Cambodia, and Indonesia. *Open Res. Eur.* **2025**, *5*, 220. [CrossRef]
51. Aseanstats. *ASEAN Statistical Brief: The Structure of ASEAN Economy*; Aseanstats.org: Jakarta, Indonesia, 2024; Volume IV. Available online: https://www.aseanstats.org/wp-content/uploads/2024/01/00.-ASEAN-Statistical-Brief-on-GDP_19Jan2024.pdf (accessed on 2 July 2026).
52. World Bank. World Development Indicators. World Bank Group. 2021. Available online: https://databank.worldbank.org/source/world-development-indicators (accessed on 2 July 2026).
53. Cruz-Jesus, F.; Oliveira, T.; Bacao, F. Digital divide across the European Union. *Inf. Manag.* **2012**, *49*, 278–291. [CrossRef]
54. Acatech Working Group Industrie 4.0.: Recommendations for Implementing the Strategic Initiative Industrie 4.0 (Final Report) 2013. Available online: http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Material_fuer_Sonderseiten/Industrie_4.0/Final_report__Industrie_4.0_accessible.pdf (accessed on 24 July 2024).
55. Wati, D.A.R.; Čaplánová, A.; Darmo, L. Identification of digital divide across Indonesian provinces: The analysis of key factors. *Statistika* **2024**, *104*, 185–202. [CrossRef]
56. Ing, L.Y.; Markus, I. *ASEAN Digital Community 2040; Policy Brief No. 2022-11*; Economic Research Institute for ASEAN and East Asia (ERIA): Jakarta, Indonesia, 2023.
57. Hendratmoko, S. ASEAN's digital integration: Strategic management, challenges, opportunities, and the role of new technologies. *J. Ekon. Bisnis Digit. (MINISTAL)* **2023**, *2*, 1271–1286. [CrossRef]
58. Mahboub, H.; Sadok, H.; Chehri, A.; Saadane, R. Measuring the Digital Transformation: A Key Performance Indicators Literature Review. *Procedia Comput. Sci.* **2023**, *225*, 4570–4579. [CrossRef]
59. Zou, L.; Li, W.; Wu, H.; Liu, J.; Gao, P. Measuring Corporate Digital Transformation: Methodology, Indicators and Applications. *Sustainability* **2024**, *16*, 4087. [CrossRef]
60. Sprengel, A.; Ulrich, P.S.; Rieg, R. Analyzing Multidimensional Maturity Models in Digital Transformation Research. In *AMCIS 2024 Proceedings. 2*; AIS eLibrary: Atlanta, GA, USA, 2024. Available online: https://aisel.aisnet.org/amcis2024/stratcompis/stratcompis/2 (accessed on 2 July 2026).
61. World Bank. World Development Report 2016: Digital Dividends. 2016. Available online: https://openknowledge.worldbank.org/bitstream/handle/10986/23347/9781464806711.pdf (accessed on 2 July 2026).
62. International Telecommunication Union. Measuring the Information Society Report 2017. ITU, 2017. Available online: https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2017/MISR2017_ES_E.pdf (accessed on 2 July 2026).
63. International Telecommunication Union. Consultation on the ICT Development Index 2019. Available online: https://www.itu.int/en/ITU-D/Statistics/Documents/IDI2019consultation/BDT_Cir_026_DKH_IDA_E.pdf (accessed on 2 July 2026).
64. United Nations. *E-Government Survey 2024: Accelerating Digital Transformation for Sustainable Development (with Addendum on Artificial Intelligence)*; United Nations Department of Economic and Social Affairs, United Nations: New York, NY, USA, 2024. Available online: https://desapublications.un.org/sites/default/files/publications/2024-09/%28Web%20version%29%20E-Government%20Survey%202024%201392024.pdf (accessed on 2 July 2026).
65. ASEAN Digital Integration Index (ADII) Report 2021. Measuring Digital Integration to Inform Economic Policies. ASEAN Secretariat 2021. Available online: https://asean.org/wp-content/uploads/2021/09/ADII-Report-2021.pdf (accessed on 2 July 2026).
66. International Monetary Fund. Southeast Asia Economic Profile (DataMapper). Available online: https://www.imf.org/external/datamapper/profile/SEQ (accessed on 18 June 2024).

67. Su, J.; Dong, C.; Su, K.; He, L. Research on the construction of digital economy index system based on K-means-SA algorithm. *SAGE Open* **2023**, *13*, 21582440231216359. [CrossRef]
68. Australian Government. ASEAN-Australia Comprehensive Economic Framework. Available online: https://aseanaustralia.pmc.gov.au/sites/default/files/asean-cef.pdf (accessed on 18 June 2024).
69. The Polish Institute of International Affairs: Prospects for the Development of the EU–ASEAN Strategic Partnership. Available online: https://pism.pl/publikacje/perspektywy-rozwoju-partnerstwa-strategicznego-ue-asean (accessed on 2 July 2026).
70. Sarra, A.; Nissi, E.; Evangelista, A.; Di Battista, T. A Functional approach for constructing dynamic Composite Indicators. *Stat. Methods Appl.* **2024**, *33*, 173–204.
71. Troyanskaya, O.; Cantor, M.; Sherlock, G.; Brown, P.; Hastie, T.; Tibshirani, R.; Botstein, D.; Altman, R.B. Missing value estimation methods for DNA microarrays. *Bioinformatics* **2001**, *17*, 520–525. [CrossRef] [PubMed]
72. Hellwig, Z. Zastosowanie metody taksonomicznej do typologicznego podziału krajów ze względu na poziom ich rozwoju oraz zasoby i strukturę wykwalifikowanych kadr. *Przegląd Stat.* **1968**, *15*, 307–327.
73. Greco, S.; Ishizaka, A.; Tasiou, M.; Torrisi, G. On the methodological framework of composite indices: A review of the issues of weighting, aggregation, and robustness. *Soc. Indic. Res.* **2019**, *141*, 61–94. [CrossRef]
74. Saisana, M.; Saltelli, A.; Tarantola, S. Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators. *J. R. Stat. Soc. Ser. A Stat. Soc.* **2005**, *168*, 307–323. [CrossRef]
75. Ward, J.H. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* **1963**, *58*, 236–244. [CrossRef]
76. Rousseeuw, P.J. Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *J. Comput. Appl. Math.* **1987**, *20*, 53–65. [CrossRef]
77. Caliński, T.; Harabasz, J. A dendrite method for cluster analysis. *Commun. Stat.* **1974**, *3*, 1–27. [CrossRef]
78. Sala-i-Martin, X.X. The classical approach to convergence analysis. *Econ. J.* **1996**, *106*, 1019–1036. [CrossRef]
79. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2025. Available online: https://www.R-project.org/ (accessed on 2 July 2026).
80. Maechler, M.; Rousseeuw, P.; Struyf, A.; Hubert, M.; Hornik, K. *Cluster: Cluster Analysis Basics and Extensions. R Package Version 2.1.8.1*; Comprehensive R Archive Network (CRAN): Vienna, Austria, 2025.
81. Bhat, K.S.; Kiruthika, C. Silhouette: Proximity Measure Based Diagnostics for Standard, Soft, and Multi-Way Clustering. R package version 0.9.6. *Res. Squar.* **2025**. [CrossRef]
82. Python Software Foundation. *Python Language Reference*, version 3.12; Python Software Foundation: Wilmington, DE, USA, 2010. Available online: http://www.python.org (accessed on 2 July 2026).
83. Seabold, S.; Perktold, J. Statsmodels: Econometric and statistical modeling with python. In Proceedings of the 9th Python in Science Conference, Austin, TX, USA, 28 June–3 July 2010.
84. Pociecha, J.; Podolec, B.; Sokołowski, A.; Zając, K. *Metody Taksonomiczne w Badaniach Społeczno-Ekonomicznych/Taxonomic Methods in Socio-Economic Research*; PWN: Warszawa, Poland, 1988.
85. Evans, R. *Clustering for Classification*; OmniScriptum GmbH & Co. KG: Chișinău, Moldova, 2008.
86. Ott, R.L.; Longnecker, M. *An Introduction to the Statistical Methods and Data Analysis*; Cengage: Boston, MA, USA, 2021.
87. AMRO. *ASEAN +3 Regional Economic Outlook*; ASEAN+3 Macroeconomic Research Office: Singapore, 2025.
88. ADB. *Annual Report 2025. Solving Complex Challenges Together Scaling Up for Impact*; Asian Development Bank: Manila, Philippines, 2026.
89. World Bank. *Digital Progress and Trends Report 2023*; World Bank: Washington, DC, USA, 2024.
90. ITU. *Measuring Digital Development Facts and Figures 2023*; ITU: Geneva, Switzerland, 2023.
91. ASEAN. *ASEAN Digital Masterplan 2025*; ASEAN: Jakarta, Indonesia, 2021.
92. Suntherasegarun, S.; Najmi, A.; Sachdev, P.K.; Youganesparan, N. *Challenges and Opportunities for ASEAN MSME Trade—Insights from the Food and Beverage Industry*; API Report no. 10; Friedrich Naumann Foundation of Freedom Regional Office for Southeast and East Asia: Bangkok, Thailand, 2025. Available online: https://www.ideas.org.my/publications/asean-integration-report-2025-challenges-and-opportunities-for-asean-msme-trade-insights-from-the-food-and-beverage-industry/ (accessed on 2 July 2026).
93. UNCTAD; ASEAN Secretariat. *ASEAN Investment Report 2024*; UNCTAD: Geneva, Switzerland; ASEAN Secretariat: Jakarta, Indonesia, 2024.
94. ASEAN+3 Macroeconomic Research Office (AMRO). *ASEAN: Regional Economic Outlook, 2024*; ASEAN+3 Macroeconomic Research Office (AMRO): Singapore, 2024.

95. Oikawa, K.; Iwasaki, F.; Ueki, Y.; Urata, S. Digital divide among firms in ASEAN before, during, and after the COVID-19 pandemic. In Proceedings of the 24th Biennial Conference of the International Telecommunications Society (ITS): "New Bottles for New Wine: Digital Transformation Demands New Policies and Strategies", International Telecommunications Society (ITS), Calgary, Seoul, Republic of Korea, 23–26 June 2024.
96. Economic Research Institute for ASEAN and East Asia (ERIA). *ASEAN Vision 2040: Towards a Bolder and Stronger ASEAN Community*; Economic Research Institute for ASEAN and East Asia: Jakarta, Indonesia, 2019.