“THE ADAPTIVE HELIX MODEL AS A CATALYST FOR THE GROWTH OF THE DIGITAL AND GREEN ECONOMIES”

Research Paper

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“Abstract”

This article introduces the Adaptive Helix Model (AHM) as a critical framework for advancing digital and green economies. Building on the evolution of helix models, AHM embeds adaptability across eight interconnected helices: Strategic Alignment, Governance Leadership, Venture Finance, Knowledge Dynamics, Economic Ecosystem, Techno-Ecosystems, Eco-Communication, and Society & Sustainability. The study identifies key challenges facing Innovation Zones and Ecosystems (IZEs), including financing, governance, industrial transformation, infrastructure disparities, labor dynamics, data security, and environmental pressures. It demonstrates how AHM provides structured pathways to address these challenges through agile governance, sustainable capital flows, talent development, ecosystem diversification, and resilient digital–physical infrastructure, complemented by transparent communication and inclusive adoption. Furthermore, the article argues that adaptivity is not only a theoretical advancement but also a practical necessity. It examines the potential challenges and risks associated with implementing AHM and suggests preventive and proactive strategies to ensure smooth, successful, effective, and growth-supporting implementation.

Keywords: Adaptive Helix Model, Innovation Zones and Ecosystems, Digital and Green Economy, Sustainability and Adaptivity.

1 Introduction

Numerous countries aim to develop and invest in Innovation Zones and Ecosystems (IZEs), as these are crucial for achieving economic excellence (Adu McVie et al., 2023). The results indicated that creating economic zones focused on specific areas, such as the digital or green economy, as well as innovative sectors like green technologies or high-tech innovations, boosts innovation. This is evident in the increase in research activities, patent registrations, and the ongoing emergence of new research fields (Wu, Liu and Huang, 2021). Despite the rapid growth of both the digital economy and the green economy, the growth rate of the digital economy surpasses that of the green economy (Wang et al., 2025). This discrepancy has resulted in several economic challenges that could impede the establishment of an innovation zone and hinder the achievement of economic goals. Additionally, it has led to various environmental and social issues (Cao, 2024; Raihan, 2024). Many innovation regions depend on established models to foster innovation and economic growth, including the triple helix, quadruple helix, quintuple helix, and N-Tuple helix frameworks. However, these models often face several challenges. They frequently lack alignment between theoretical research and market needs, suffer from complexity, and feature unclear governance. Additionally, there can be tensions between sustainability goals and economic interests, along with various regulatory issues such as structural imbalances and coordination problems among key stakeholders. Moreover, these

frameworks may not adequately connect to indicators tailored to the specific innovation region and the types of innovations it promotes. To address these challenges, the Adaptive Helix Model (AHM) is proposed as a more effective solution (Pique, Miralles and Mirabent, 2019; Feng, Yan and Zhang, 2021; Stundziene et al., 2024; Alnouman, 2025). How can AHM be applied to redesign and restructure IZEs to enhance their capacity for fostering inclusive growth within the digital and green economy? This article reviews AHM and examines the key challenges confronting the digital and green economy. The effectiveness of AHM in addressing these challenges and in fostering the advancement of the digital and green economy will be demonstrated. In conclusion, the primary obstacles that organizations may encounter during the implementation of AHM will be outlined, along with crucial preventative and proactive strategies to navigate these risks and challenges and ensure a smooth implementation process.

2 Literature Review

innovation zones are powerful interconnected environments that drive innovation through effective collaboration among universities, companies, startups, investors, and government entities. The innovation ecosystem encompasses the broader network of these key players and resources, while an innovation zone serves as a concentrated hub that accelerates this dynamic activity. Together, they create a vibrant environment where ideas are generated, developed, and successfully commercialized, empowering cities and regions to enhance their innovation capacity and adeptly adapt to economic and technological changes. The terminology of innovation zones and ecosystems (IZEs) is intentional, as AHM applies to both concepts (Mercan and Göktaş, 2011; Peek, Clark and Moonen, 2016).

The digital economy and IZEs are closely linked, as the digital economy provide essential frameworks and tools, such as digital technologies and infrastructure, for these zones to flourish. IZEs are designated areas to foster innovation and economic growth, attracting investment and talent in advanced technologies like e-commerce, digital marketing, digital financial services, software development, computer games, and cloud services (Mao et al., 2024). The digital economy is recognized as a key driver of economic growth and development in many advanced countries, continually expanding due to its significant influence on economic and business activities. The synergy between the digital economy and IZEs stimulates new business opportunities, enhances efficiency, and encourages a culture of innovation, all of which contribute to overall economic development and competitiveness (Xia, Baghaie and Sajadi, 2024).

Comparing the digital and green economies reveals a consistent pattern that facilitates the development of an interconnected system between them. The impact of the digital economy on GDP varies significantly based on factors such as resource dependence, geographic location, financial development, and openness. This variation is driven by green technological innovation, modernization of industrial structures, and energy conservation. The findings indicate that the digital economy not only fosters growth in the green economy but also substantially enhances the overall productivity of green factors of production (Xiao et al., 2023; Li et al., 2024, 2025; Reznikova, 2024).

Given the challenges of climate change, global population growth, and changes in the global economy, it is crucial to embrace more sustainable models of production and consumption. This shift aims to reduce the use of natural resources and greenhouse gas emissions, leading us towards low-carbon societies and a green economy (Albino, 2013).

IZEs are conceptual frameworks describing dynamic, evolving networks of actors, institutions, and resources that collectively generate innovation. They emphasize collaboration, competition, co-creation, and knowledge flows across universities, industry, governments, civil society, and environmental actors. Their scope is broad, regional, national, or even global. IZEs are spatially defined areas, such as science parks, clusters, special economic zones, and innovation districts, that serve as physical anchors for innovation. They focus on infrastructure, investment, and regulatory incentives that enable experimentation, commercialization, and scaling of new technologies. In practice, IZEs represent the integration of these two perspectives: the spatial platforms of zones with

the dynamic networks of ecosystems. This dual lens highlights that zones can act as catalysts, but their long-term effectiveness depends on embedding them within broader ecosystems of collaboration, governance, and market linkages. Importantly, models for organizing innovation and generating economic return are applied in IZEs. These frameworks provide theoretical and practical tools for structuring the interactions between diverse stakeholders and aligning innovation with national transformation strategies (Smorodinskaya et al., 2017; Carayannis et al., 2018; Granstrand and Holgersson, 2020; Nyamaka et al., 2020; Wu, Li and Huang, 2024)

The Helix Model of Innovation was first conceived to explain how interactions among multiple actors could generate new knowledge and promote economic and social development (Weingart, 1997; Godin, 1998). The earliest version, the Double Helix, described collaboration between academia and industry as a driver of innovation and growth. This evolved into the Triple Helix Model, formally developed by Etzkowitz and Leydesdorff in the 1990s, which emphasized the interplay of universities, industry, and government (Etzkowitz and Leydesdorff, 2000; Leydesdorff, 2012; Carayannis and Campbell, 2021). Despite its influence, the Triple Helix faced challenges, including mismatches between theoretical academic research and market-oriented industrial needs, divergent timelines, regulatory constraints, and institutional rigidity (Shinn, 2002; Leydesdorff, 2012). To address broader societal roles, the Quadruple Helix Model was proposed in 2009, adding civil society and media as key actors (Leydesdorff, 2012). However, it struggled with public engagement, conflicting goals between societal ethics and industry profits, and the lack of standardization (Mineiro, Assis De Souza and Carvalho De Castro, 2021). The Quintuple Helix Model then integrated the natural environment, reflecting the sustainability agenda and socio-ecological transformation (Carayannis, Barth and Campbell, 2012a, 2012b; Durán-Romero et al., 2020; Kholiavko et al., 2021; Zen and Shibakawa, 2022; Dewika et al., 2024). Yet tensions persisted between sustainability and profitability, as well as difficulties in measuring eco-innovation impacts (Zhou and Etzkowitz, 2021; Cai, 2022). Most recently, the N-Tuple Helix Model sought to incorporate emerging domains such as global finance, cybersecurity, digital transformation, and AI (Carayannis and Campbell, 2010; Leydesdorff, 2012; Fitjar, Gjelsvik and Rodríguez-Pose, 2014; Villarreal and Calvo, 2015; Carayannis et al., 2018; Roman et al., 2020). However, this model has been criticized for excessive complexity, unclear governance, and difficulties in sustaining stakeholder coordination and commitment (Donati, Stefani and Bellandi, 2023; Sloup, Riedl and Machoň, 2023; Haryadi, Sulistyadi and Asmoro, 2025).

The AHM extends earlier helix frameworks by offering a more flexible and context-sensitive approach to building IZEs. Unlike the Triple, Quadruple, or Quintuple Helix models, which can be rigid or fragmented, the AHM introduces eight interconnected helices: Strategic Alignment, Governance, Finance, Knowledge, Economy, Technology, Communication, and Society. These helices operate in a continuous loop, organized into foundational and expansion phases, allowing ecosystems to recalibrate dynamically in response to economic, technological, or environmental change. By integrating governance, finance, technology, and societal dimensions, the AHM enables IZEs to overcome structural weaknesses, align diverse stakeholders, and remain resilient. It serves both as a diagnostic tool for identifying gaps and as a framework for implementation of adaptive, sustainable innovation strategies (Alnouman, 2025).

3 Research Approach

This article adopts a conceptual and qualitative research design, suitable for examining emerging frameworks like AHM that have not yet been fully operationalized or tested empirically. The approach proceeds in three stages: (1) Identification of Challenges. Drawing from the latest academic and policy literature on the digital and green economies, the study synthesizes key challenges facing IZEs. This establishes the empirical problem space. (2) Examination of AHM's Potential, using a conceptual mapping method, the study positions AHM's eight helices against these challenges to assess how the model addresses governance, finance, talent, infrastructure, and sustainability gaps. (3) Anticipating Implementation Barriers, the study applies a critical lens to explore potential obstacles IZEs may

encounter when adopting AHM, drawing from case-based illustrations to maintain practical relevance. This multi-step, theory-driven approach allows the article to advance both conceptual clarity and practical guidance. It is appropriate at this stage of AHM's development, where the priority is to define its contribution to provide insights into both its applicability and its practical constraints.

4 The Adaptive Helix Model

The AHM is a transformation-driven framework for designing and managing IZEs. It was developed in response to the limitations of earlier helix-based models -Triple, Quadruple, Quintuple, N-Tuple, and others- which often prove rigid, fragmented, or overly complex for dynamic, decentralized innovation environments.

At its core, the model introduces eight interconnected helices that function in a continuous application loop organized into two phases: Foundation (establishing with strategic alignment, governance leadership, venture finance, and knowledge dynamics) and Expansion (economic ecosystem, techno-ecosystems, eco-communication, and society & sustainability). Unlike static frameworks, AHM allows components to be adjusted, combined, or emphasized based on the specific context of the ecosystem, offering both customization and adaptability.

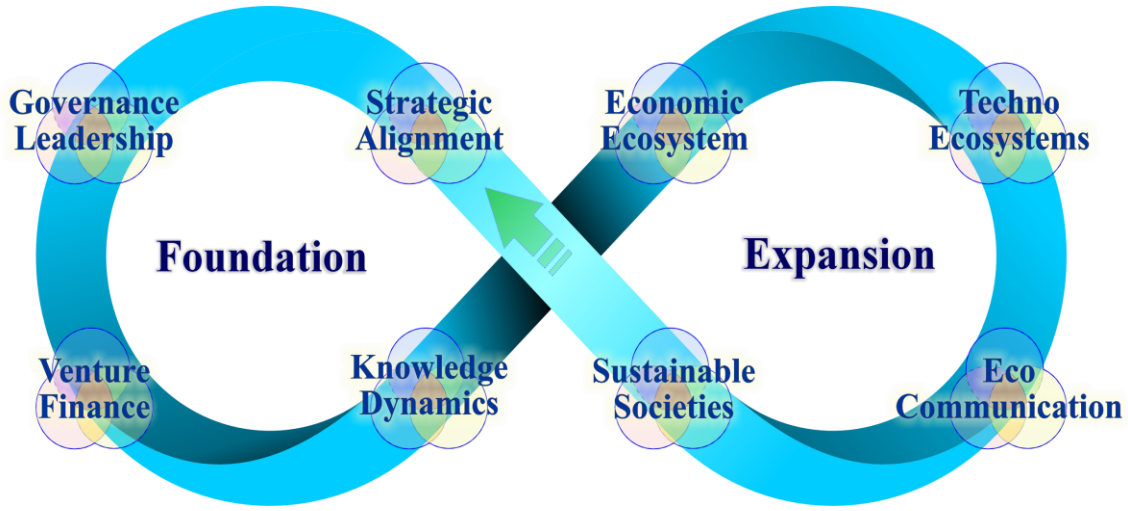

Figure 1. The Adaptive Helix Model (Source: Alnouman, 2025, p.4)

4.1 AHM components

As shown in Figure 1, AHM consists of eight successive spirals, each consisting of three components that combine to form the spiral. These eight spirals are:

1. Strategic Alignment: establishes vision, adaptive planning, performance metrics, and ecosystem mapping.
2. Governance Leadership: ensures transparent, agile, and globally aligned governance, including regulatory experimentation.
3. Venture Finance: builds diverse funding mechanisms, incubation and acceleration support, and sustainable investment practices.
4. Knowledge Dynamics: integrates R&D, education, knowledge transfer, and talent development.
5. Economic Ecosystem: aligns innovation with market competitiveness, entrepreneurship, and circular economy models.

6. Techno-Ecosystems: embeds digital and physical infrastructure (AI, IoT, 5G, smart systems) into innovation environments.
7. Eco-Communication: fosters media, science communication, environmental awareness, and alignment with the UN Sustainable Development Goals.
8. Society & Sustainability: emphasizes inclusivity, ethics, cultural adoption, and human-centric technological integration (Society x.0).

4.2 Key AHM features

By addressing gaps in previous helix models, such as strategic misalignment, rigid governance, fragmented funding, and weak entrepreneurial culture, AHM provides a comprehensive framework for building IZEs that are resilient, inclusive, and sustainable. It positions IZEs as adaptive platforms capable of driving long-term value creation and navigating global uncertainty.

- Flexibility and Modularity: Components can be adapted to fit diverse institutional or geographic contexts.
- Systemic Integration: Ensures alignment across strategy, governance, funding, knowledge, economy, technology, communication, and society.
- Resilience and Scalability: Supports real-time recalibration, enabling ecosystems to evolve with changing economic, social, or environmental conditions.
- Diagnostic and Implementation Tool: Serves as a practical guide for identifying structural gaps, prioritizing actions, and sequencing development.

5 Challenges of the Digital and Green Economy

IZEs are central to driving digital and green transitions. However, they face interconnected risks that can seriously undermine their potential for sustainable growth. These challenges vary in significance; some present immediate threats to economic stability and competitiveness, while others exacerbate long-term vulnerabilities.

5.1 Financing and scaling disruptive innovation

IZEs face persistent barriers in mobilizing capital for disruptive innovation. Capital markets remain highly risk-averse toward immature green technologies, such as hydrogen or carbon capture and storage (CCS), creating funding gaps for projects that require long-term commitment. Renewable energy ventures are especially capital-intensive and often depend on external expertise, which can undermine local ownership and social acceptance. As a result, many IZEs default to incremental improvements rather than transformative investments. Yet, incremental gains are insufficient to meet pressing climate challenges; hard-to-abate sectors like steel, cement, and transportation demand bold commitments to radical innovation (Söderholm, 2020; Xiaole and Piscunova, 2022). Without structural mechanisms to align Financing and Scaling Disruptive Innovation, IZEs risk stagnation and diminished impact.

5.2 Fragmented governance and weak measurement

IZEs must adopt robust multi-level governance that links local, national, and international frameworks. Yet, fragmented policies for green and digital innovation often create misaligned incentives across government, industry, and civil society. Many IZEs lack comprehensive performance metrics, reporting primarily on job creation and investment while neglecting critical outcomes such as carbon intensity reduction, digital inclusion, and societal value. This gap undermines their alignment with the Sustainable Development Goals (SDGs). A 2023 OECD review found that fewer than 30% of

innovation districts publish integrated performance reports, exposing a serious weakness in accountability and effectiveness (Söderholm, 2020; Shabur, 2024). Without coherent governance and measurement, IZEs risk failing to deliver transformative outcomes.

5.3 Concentration of market power and industrial changes

IZEs that depend heavily on dominant digital platforms risk reinforcing monopolistic structures that limit opportunities for local small and medium-sized enterprises (SMEs). Such concentration of market power suppresses innovation, reduces industrial diversity, and weakens incentives for sustainable practices. Firms within IZEs also face the strategic uncertainty of balancing profitability with environmental commitments, a tension that "business-as-usual" models cannot resolve. Without structural interventions, IZEs risk perpetuating dependence on global digital giants while failing to deliver the radical innovation required for sustainability (Söderholm, 2020; Rosário and Dias, 2023; Wang, 2024; Wang et al., 2024).

5.4 Regional disparities in capacity and infrastructure

IZEs operate on highly uneven terrain. Digital infrastructure, innovation capacity, and financial resources are disproportionately concentrated in advanced regions, producing vastly different outcomes from similar policy measures. Empirical evidence shows that in technologically advanced areas, the digital economy provides a strong multiplier effect on green growth, while in less developed regions, this effect is minimal or absent. Such disparities stem from weaker infrastructure, talent shortages, and shallow market depth, which prevent lagging regions from converting digitalization into meaningful green outcomes. As a result, benefits accumulate in advanced areas, while less developed zones remain marginalized, undermining inclusive growth and widening structural divides (Wang et al., 2024).

5.5 Labor, skills, and social dynamics

IZEs can unintentionally deepen inequality, particularly in regions with weak infrastructure and low digital literacy. For example, while 80% of individuals in developed economies are online, only 15% in less developed nations have access, excluding large populations from digital–green opportunities. At the same time, automation within IZEs disrupts labor markets by displacing mid- and low-skill jobs in agriculture and manufacturing, raising risks of structural unemployment. Green transitions also often skew benefits toward higher-income groups through mechanisms such as solar panel adoption or electric vehicle subsidies, while lower-income households face disproportionate burdens from carbon and energy taxes. These dynamics reinforce social divides, eroding the inclusivity of IZEs (Söderholm, 2020; Rosário and Dias, 2023; Wang, 2024).

5.6 Data security and digital trust

IZEs rely extensively on interconnected data-sharing systems to operate effectively. However, this dependence increases their vulnerability to breaches and cyberattacks. In 2022 alone, more than 422 million sensitive records were exposed in U.S. breaches, with the average cost per incident reaching $4.45 million. Verizon's 2023 report further revealed that 74% of breaches involve human factors, such as phishing or insider misuse, underscoring how human error compounds systemic weaknesses. For IZEs, such breaches erode digital trust and can stall the adoption of green and digital innovations, making data security and privacy not just technical necessities but critical enablers of legitimacy and resilience (Rosário and Dias, 2023; Raihan, 2024; Wang, 2024).

5.7 Environmental and resource pressures

IZEs are critical hubs for technological advancement but also generate heavy environmental pressures. They rely on energy-intensive digital infrastructure such as data centers, laboratories, and industrial clusters, directly undermining sustainability goals. Data centers alone consumed 200 terawatt-hours (TWh) of electricity in 2020, around 1% of global use, with projections suggesting this figure could rise to 8% by 2030. IZEs also contributes to the mounting problem of electronic waste: in 2019, global e-waste reached 53.6 million metric tons, yet only 17.4% was recycled. Hazardous disposal methods, including acid baths, release toxins into surrounding communities, compounding public health risks. Without systemic solutions, IZEs risk worsening both environmental degradation and social harm (Söderholm, 2020; Rosário and Dias, 2023).

6 How AHM Tackles and Conquers Challenges

6.1 Financing and scaling disruptive innovation

AHM effectively tackles barriers to innovation funding by seamlessly integrating the Venture Finance Helix, the Techno-Ecosystems Helix, and the Economic Ecosystem Helix. This strategic alignment ensures that funding is not only in sync with technological advancements but also with market readiness, transforming fragmented financing into a coherent force that accelerates the scaling of disruptive innovations. In response to recent volatility in global capital markets, including a significant 60% decline in venture funding since 2021, AHM employs the Strategic Alignment Helix for proactive, foresight-driven planning. Simultaneously, it leverages the Eco-Communication Helix to enhance transparency and bolster stakeholder confidence. The success of this model is exemplified by Toronto's MaRS Discovery District, which demonstrates how multi-stakeholder platforms can effectively channel capital into high-impact sectors like cleantech and digital technologies (Fitzgerald, Anderson and Kula, 2010). AHM builds on this logic by combining Governance Leadership, which emphasizes policy agility, with Venture Finance focused on sustainable investment and Knowledge Dynamics that cultivate entrepreneurial talent. This ensures that IZEs prioritize ventures with transformative potential. With this adaptive integration, IZEs are poised to overcome fragmented financing, mitigate risks, and cultivate the capacity to scale disruptive technologies across various sectors. The future of innovation funding is clearer and more robust than ever.

6.2 Fragmented governance and weak measurement

AHM overcomes governance and measurement gaps by embedding adaptivity into policy and oversight structures. The Strategic Alignment Helix establishes dual transformation metrics, integrating digital adoption with sustainability goals. The Governance Leadership Helix ensures agile, multi-level decision-making that can recalibrate policies in response to shifting contexts. The Eco-Communication Helix fosters transparency by aligning reporting practices with SDGs, building legitimacy and public trust. Together, these helices create continuous policy–measurement–learning loops, transforming governance from compliance-driven to evidence-based and adaptive. IZEs, often vulnerable to shocks like regulatory shifts or crises, can use AHM’s foresight and resource reallocation mechanisms to realign strategies quickly. Finland’s Mission Zero Carbon 2035 exemplifies this adaptive approach, where iterative policy adjustments are tied to measurable climate goals (Huttunen et al., 2019, 2022). AHM systematizes such practices, offering IZEs a pathway to mission-driven transformation with built-in accountability and resilience.

6.3 Concentration of market power and industrial changes

AHM addresses structural imbalances by integrating the Governance Leadership Helix, which enforces competition policies and prevents monopolistic dominance; the Venture Finance Helix,

which prioritizes funding streams for SMEs and startups; and the Economic Ecosystem Helix, which promotes industrial diversification and resilience. This alignment reduces reliance on dominant digital platforms while empowering local firms to scale and compete. AHM also ensures resilience against platform dependency by embedding transparent stakeholder dialogue and adaptive regulation. A practical illustration is the European Union's Digital Markets Act (DMA), which curtails excessive platform power and ensures fair market access (Gosztonyi and Zankova, 2023). By embedding these adaptive mechanisms, IZEs can transition from dependency-driven structures to diversified industrial ecosystems, achieving both competitiveness and sustainability.

6.4 Regional disparities in capacity and infrastructure

AHM mitigates regional disparities by combining the Knowledge Dynamics Helix (talent development and knowledge transfer), the Economic Ecosystem Helix (industrial diversification), and the Strategic Alignment Helix (national–regional policy coherence). This ensures that resources are redistributed, and weaker zones are integrated into broader innovation networks. During global shocks, such as supply chain disruptions, AHM activates the Venture Finance Helix to direct targeted investments and the Eco-Communication Helix to strengthen local trust and legitimacy. Evidence from China's digital economy illustrates these disparities: eastern provinces leverage advanced infrastructure for green growth, while central and western regions struggle to keep pace struggle (Chen et al., 2025; Tong and Tang, 2025; Zhang, Wu and Chen, 2025). AHM addresses this imbalance by further integrating the Governance Leadership, Techno-Ecosystems, and Society & Sustainability Helices, enabling tailored interventions that connect lagging regions to national innovation strategies, ensuring balanced digital–green development.

6.5 Labor, skills, and social dynamics

AHM addresses these challenges through three components: the Knowledge Dynamics Helix (reskilling, entrepreneurship, and education), the Society & Sustainability Helix (citizenship, inclusion, and well-being), and the Economic Ecosystem Helix (new industries and entrepreneurship). This framework incorporates social equity into IZEs, promoting inclusive development alongside technological progress. Rapid advancements, such as in artificial intelligence, can disrupt labor markets, but AHM offers a proactive strategy to manage these transitions, engaging the Strategic Alignment Helix (scenario foresight and adaptive planning), the Society & Sustainability Helix (citizen participation), and the Eco-Communication Helix (transparent engagement). Germany's dual vocational training system exemplifies how innovation-driven economies can mitigate automation's impacts (Wieland, 2015; Zuo, Zhang and Huang, 2025).By embedding adaptive pathways across multiple helices, AHM positions IZEs as platforms that enhance rather than erode social equity (Söderholm, 2020; Rosário & Dias, 2023; Wang, 2024).

6.6 Data security and digital trust

AHM tackles data-related vulnerabilities through an integrated, multi-helix approach. The Techno-Ecosystems Helix strengthens digital infrastructure, AI governance, and cybersecurity safeguards, while the Governance Leadership Helix enforces adaptive privacy standards aligned with international best practices. At the same time, the Eco-Communication Helix builds transparency by promoting clear accountability in data usage, and the Society & Sustainability Helix fosters citizen trust by embedding rights protection into system design. In the event of cyberattacks, AHM enhances resilience by activating the Strategic Alignment Helix for scenario planning and rapid policy recalibration. Estonia's X-Road platform offers a strong example: its decentralized architecture enables secure, auditable data exchange while giving citizens visibility over who accesses their information (Paide et al., 2018). By embedding such adaptive practices, AHM ensures that privacy, security, and trust are foundational to IZEs, enabling them to scale digital–green innovation without eroding legitimacy.

6.7 Environmental and resource pressures

AHM addresses these pressures by embedding sustainability into its structural design. The Techno-Ecosystems Helix advances energy-efficient technologies and circular product design, while the Economic Ecosystem Helix promotes green value chains that decouple growth from resource depletion. The Society & Sustainability Helix ensures cultural adoption of sustainable practices, anchoring public legitimacy. To enhance resilience, the Strategic Alignment Helix deploys foresight and scenario planning, enabling IZEs to adapt under conditions such as extreme heatwaves or resource shocks. The European Union's Circular Economy Action Plan illustrates how coordinated recycling, eco-design, and emissions reduction can alleviate environmental pressures (Haukkala, 2025). AHM strengthens this by activating the Governance Leadership Helix for policy coherence, the Venture Finance Helix for channelling green capital, and the Eco-Communication Helix for transparent reporting. Together, these mechanisms ensure IZEs become engines of sustainable innovation while protecting environmental and societal well-being.

7 AHM As a Catalyst for the Digital and Green Economy

The AHM confidently drives the digital and green economy by providing a comprehensive, dynamic, and integrated framework that effectively addresses the common challenges faced by IZEs. Its strength lies in eight interconnected helices, all working in harmony to create a resilient, adaptable, and purpose-driven environment for sustainable innovation:

7.1 Strategic alignment for dual transformation

The Strategic Alignment Helix is the foundation of AHM, ensuring that IZEs integrate both digital and environmental objectives into their core strategies. Through the Strategic Innovation Framework, this helix enables IZEs to anticipate technological disruptions and ecological challenges effectively. The Impact & Performance Metrics component establishes key performance indicators (KPIs) to track progress in digital adoption, such as AI integration and data utilization, alongside green outcomes like carbon reduction. The Typology & Ecosystem Mapping component identifies innovative opportunities at the intersection of digital and environmental initiatives, including AI for resource optimization and IoT-enabled energy grids. A notable example is the European Green Deal and Digital Compass, aligning sustainability targets with digital advancements to achieve climate neutrality by 2050 (eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0118, 2021). This alignment showcases how the Strategic Alignment Helix drives economic growth through interconnected pathways for digitalization and sustainability.

7.2 Adaptive and agile governance

The Governance Leadership Helix of AHM is essential for enabling IZEs to effectively balance rapid digital experimentation with sustainability commitments. By leveraging Regulatory Agility & Policy Experimentation, IZEs establish "sandboxes" where emerging digital solutions, like FinTech platforms and IoT applications, are tested under guided frameworks that require environmental assessments. This fosters innovation while ensuring ecological responsibility. Additionally, the Geopolitical & International Organizations component ensures that IZE governance conforms to global standards, including key digital regulations (such as GDPR) and sustainability agreements (like the Paris Agreement). A notable example is the UK's Financial Conduct Authority (FCA) Regulatory Sandbox, which has successfully allowed firms to trial innovative products—such as blockchain for green bonds and AI-driven ESG investment platforms—under close oversight (Zetzsche et al., 2017). This framework not only drives economic growth but also integrates digital and green transitions into adaptable governance structures aligned with global standards.

7.3 Directing capital towards sustainable digital ventures

The Venture Finance Helix, a vital part of AHM, effectively directs capital toward ventures that promote digital innovation and green transformation. It channels venture capital, grants, and decentralized finance (DeFi) into startups focused on GreenTech, CleanTech, and digital sustainability solutions. By adhering to ESG (Environmental, Social, and Governance) principles, the Financial Risk Management and Sustainable Investment component ensures that projects are evaluated for both financial returns and their environmental and social impact. Incubators and Accelerators provide crucial mentorship and resources to help these startups scale their technology and sustainable business models. A notable example is the EU Sustainable Finance Taxonomy and the NextGenerationEU Fund, which prevent greenwashing by defining sustainable economic activity. By investing a significant portion of the €800 billion recovery fund into projects that meet digital and green criteria, the EU demonstrates how the Venture Finance Helix can drive substantial capital allocation for resilient and sustainable growth (Regulation - 2020/852 - EN - taxonomy regulation - EUR-Lex, 2020).

7.4 Building a future-ready knowledge base and talent pool

The Knowledge Dynamics Helix empowers IZEs with the human capital and intellectual resources needed to drive digital and green transformations. Its Talent & Human Capital Development component focuses on reskilling and upskilling the workforce for Industry 4.0 and 5.0 roles that merge automation, data-driven efficiency, and sustainability. The Knowledge component enhances university research in crucial areas like artificial intelligence (AI), big data, and renewable energy, while facilitating effective knowledge transfer to commercialize innovations. IZEs component fosters collaboration among universities, corporations, and startups to address complex challenges. A strong example is Singapore's SkillsFuture Initiative, which promotes lifelong learning and emphasizes both digital skills (e.g., AI, data analytics) and green competencies (e.g., sustainability management) (Gog, Tan and Tan, 2024). This initiative illustrates how the Knowledge Dynamics Helix ignites IZEs, creating a future-ready workforce and a robust base for sustainable economic growth.

7.5 Fostering synergistic economic ecosystems

The Economic Ecosystem Helix drives dynamic interactions that enhance both digitalization and sustainability, creating powerful cycles of economic productivity. Its Industrial Ecosystems component integrates digital tools into supply chains, making them smarter and more sustainable, such as using AI for logistics optimization to cut costs and carbon emissions. The Business Dynamics component promotes adaptive business models like circular economy platforms, facilitating large-scale reuse, recycling, and resource sharing. Meanwhile, the Economic Foundations component leads the shift toward sustainable economic models through real-time tracking and resource management. A standout example is the Port of Rotterdam's Digital Twin, an AI-powered replica of its operations that optimizes logistics and reduces idle times, resulting in lower fuel use and CO_2 emissions (VanDerHorn and Mahadevan, 2021). This illustrates how the Economic Ecosystem Helix effectively transforms digital adoption into greener, more competitive economic outcomes.

7.6 Deploying enabling digital and physical infrastructure

The Techno-Ecosystems Helix is the essential backbone for IZEs, integrating digital and physical infrastructures crucial for dual transformation. Its Technology component deploys advanced tools like AI, Blockchain, and IoT to drive sustainable solutions, including transparent carbon credit trading and IoT-enabled energy management. The Infrastructure & SMART Ecosystems component lays the groundwork for a digital-green economy with 5G networks and innovative urban designs that enable real-time monitoring of resources, such as smart water grids. Furthermore, the Data & Intelligence Infrastructure utilizes big data and AI to optimize sustainability outcomes, including energy demand

forecasting and public transport management. A prime example is Songdo International Business District (IBD) in South Korea, a SMART city where IoT sensors monitor resources in real time (Kim, 2022), illustrating how integrated infrastructure can effectively reduce environmental impact and showcasing the Techno-Ecosystems Helix in action.

7.7 Mainstreaming sustainability through communication and narrative

The Eco-Communication Helix effectively builds legitimacy and support for IZEs by integrating sustainability into public opinion, markets, and policymaking. Its Media & Digital Networks component utilizes modern platforms to raise environmental awareness and promote digital green solutions, creating momentum for transformative change. Additionally, the UN-SDGs & Global Impact component aligns innovation projects with the Sustainable Development Goals, providing IZEs with a compelling mission that resonates with policymakers, investors, and communities. A prime example is Denmark's State of Green, a public-private partnership that showcases Denmark's green competencies globally through digital media and storytelling to attract investments and foster international partnerships (Van Bavel and Gaskell, 2004; Anderberg and Clark, 2013). This demonstrates how the Eco-Communication Helix serves as a powerful messaging tool and catalyst, embedding sustainability at the core of innovation-driven economic growth.

7.8 Ensuring social acceptance and ethical innovation

The Society & Sustainability Helix champions inclusivity and ethical responsibility in IZEs, ensuring that the digital-green transition enhances societal well-being and reduces inequalities. The Society x.0 component promotes a human-centric vision, utilizing technologies like AI and IoT to address social challenges and expand access to green and digital economies. The Ethical & Responsible Innovation component integrates sustainability principles throughout the innovative lifecycle, focusing on responsible AI development, product longevity, and recyclability. Additionally, the Cultural & Behavioral Adoption component builds public trust by aligning innovations with cultural contexts and engaging communities. A prime example is Estonia's Digital Residency and X-Road Data Governance system, which enables secure, transparent data exchanges and empowers citizens to monitor their data usage (Wulandari, Winarno and Triyanto, 2021; Fontes, Carpentras and Mahajan, 2024). Overall, Estonia illustrates how the Society & Sustainability Helix fosters technological advancement that is ethical, inclusive, and widely accepted.

8 Implementation Considerations and Adaptive Pathways

8.1 Strategic direction, mandate, decision rights, and authority

For IZEs to flourish, a clear strategic direction supported by a strong mandate is deemed essential. Authority is defined clearly to effectively address overlapping roles and conflicting agendas among stakeholders, enhancing alignment. This proactive approach is designed to prevent issues such as fragmented decision-making, unclear ownership, and accountability challenges, ensuring that initiatives are driven to create significant economic and environmental impact. To facilitate this, a formal governance charter is recommended, which clarifies decision rights, reporting structures, and roles for each stakeholder group. This charter is to be integrated into both national policy and specific IZE legislation, making decisions binding and ensuring robust support from executive leadership. Strategic oversight can be managed effectively by the Governance Leadership Helix, with a strong emphasis placed on transparent performance monitoring. This constructive framework serves to prevent institutional drift while building legitimacy and empowering IZEs to take decisive actions in fostering digital and green economic growth.

8.2 Regulatory interoperability & permitting efficiency

The unique opportunity for advancing digital and green innovation across various jurisdictions and sectors is presented by IZEs. However, the challenges posed by fragmented regulations and extended permitting processes must be addressed for their full potential to be unlocked. Uncertainty for investors and innovators can be significantly reduced by aligning local, national, and international regulations. Frameworks for regulatory interoperability must be developed, and "fast-track" permitting procedures adhering to global standards, such as the General Data Protection Regulation (GDPR) and the Paris Agreement, should be implemented to facilitate smoother project approvals. Additionally, policy sandboxes should be expanded beyond pilot programs into permanent adaptive tools to help streamline approval times while important sustainability safeguards are maintained. This constructive approach will create a more predictable environment, accelerate implementation, and allow IZEs to be positioned as attractive hubs for sustainable digital investment. By working together to overcome these regulatory challenges, innovation that benefits both the economy and the environment can be fostered.

8.3 Measurement architecture and learning loops

The complexities of both digital and green transformations can be effectively addressed by the measurement systems designed by IZEs. Traditional Key Performance Indicators (KPIs), which often focus solely on financial or environmental outcomes in isolation, are moved beyond so that the important interactions across systems can be better captured. It is essential for robust data flows and feedback loops to be established to foster continuous learning and adaptability. A shift in focus is encouraged from merely producing polished reports to delivering impactful outcomes, preventing implementation from becoming merely symbolic. Cross-helix learning is promoted by breaking down data silos, ensuring that KPIs are regularly updated to maintain trust among investors and policymakers. Strengthening the role of IZEs as credible catalysts for systemic change can be achieved through these efforts. The Strategic Alignment Helix is positioned to serve as the foundation for a Measurement, Evaluation, and Learning (MEL) architecture that integrates cross-helix KPIs and dynamic dashboards. Concurrently, real-time data collection, open sharing, and enhanced analytical capacity are championed by the Knowledge Dynamics Helix to enable effective learning loops. This integrated approach not only enhances accountability but also fosters transparency, allowing IZEs to evolve alongside digital advancements and sustainability initiatives.

8.4 Talent pipeline, mobility & place-based frictions

The success of IZEs is closely tied to access to a skilled workforce. A thriving environment for innovation is cultivated when talent shortages in the digital and green sectors are actively addressed. Challenges such as inflexible labor markets and geographic immobility are presented, offering opportunities for improvement. Expertise and capabilities in IZEs can be enhanced through investments in education and training initiatives aimed at filling these gaps. Strong talent pipelines can be developed, reducing reliance on external talent and boosting competitiveness against regions with robust education systems and effective mobility policies. The Knowledge Dynamics Helix is seen as playing a vital role by prioritizing workforce reskilling and promoting international partnerships in higher education. Additionally, the Society & Sustainability Helix is focused on ensuring inclusivity and equitable access to resources and opportunities. More avenues for mobility can be created through supportive policies such as visa facilitation, cross-border exchange programs, and place-based incentives. By constructively addressing these challenges, a resilient talent ecosystem can be built, fostering growth in both digital and green sectors and leading to more robust innovation and a brighter future.

8.5 Incentive and financing alignment

Innovation Zones and Ecosystems (IZEs) are set to thrive through blended financing but achieving this requires overcoming the misalignment of incentives among public agencies, private investors, and philanthropic organizations. While governments prioritize regulatory compliance and social impact, private investors concentrate on financial returns, and philanthropies focus on mission-driven outcomes. This lack of alignment leads to fragmented and underutilized resources, creating significant funding gaps that impede the scaling of green and digital initiatives. Moreover, competition among stakeholders can result in short-lived projects, unnecessary duplication of efforts, or "greenwashing" investments that undermine legitimacy. To effectively tackle these issues, the Venture Finance Helix must actively coordinate blended finance platforms that seamlessly integrate public risk-sharing, private venture capital, and philanthropic grants. Additionally, the Governance Leadership Helix should establish strong policy frameworks that align incentives with shared outcomes, such as carbon reduction and digital inclusion metrics. This approach will ensure that financing is not only de-risked and mission-driven but also scalable, solidifying IZEs as trusted vehicles for sustainable digital transformation.

8.6 Capabilities and operating model for adaptivity

For AHM to be successfully implemented in IZEs, an operating model that seamlessly incorporates adaptivity into everyday practices must be built. Currently, many challenges related to skilled personnel, agile processes, and effective digital tools are being faced by IZEs, but clear pathways for improvement exist. A strong adaptive operating model should be developed to enable a shift away from rigid structures and foster a more dynamic work environment. This will involve silos among teams being broken down, processes streamlined, and digital tools fully leveraged to enhance responsiveness and drive digital–green growth. To support this transformation, continuous capability-building must be prioritized within the Knowledge Dynamics Helix, empowering staff with the adaptive skills needed for success. By offering digital platforms and decision-support tools, the Techno-Ecosystems Helix can play a vital role in encouraging real-time collaboration. Meanwhile, the Strategic Alignment Helix should focus on establishing agile processes that allow for swift adjustments in response to changing circumstances. Through the integration of these elements, a culture and operating system where adaptivity is a fundamental aspect of daily operations can be cultivated within IZEs, paving the way for innovation and sustainable growth.

9 Discussion

The Adaptive Helix Model (AHM) advances innovation frameworks by addressing the rigidity of traditional helix-based models. While Triple, Quadruple, and Quintuple Helix models broaden stakeholder inclusion, they remain structurally linear and struggle to adapt to rapid technological and ecological disruptions (Etzkowitz and Leydesdorff, 2000; Carayannis, Barth and Campbell, 2012a). AHM introduces adaptability as a core principle, enabling Innovation Zones and Ecosystems (IZEs) to recalibrate strategies, governance, and resource flows in real time. However, AHM faces challenges. Its integration of eight helices can create conceptual complexity, requiring careful prioritization to avoid decision paralysis. Adaptability may also meet resistance from institutions favoring stability. Moreover, empirical validation is limited, current support stems from conceptual mapping and illustrative cases rather than long-term data. Despite these hurdles, AHM offers a robust framework for multi-level governance that links digital and green transitions—two pressing global imperatives. By embedding adaptability, it fosters iterative learning and systemic alignment, uniting diverse stakeholders in resilient innovative environments. This makes AHM a valuable tool for policymakers, zone leaders, and researchers seeking future-ready solutions.

10 Conclusion

This article presents AHM as a next-generation framework designed to catalyze the growth of both digital and green economies. By addressing the structural, policy, financial, social, and technological challenges that impede IZEs, AHM illustrates how adaptivity can be integrated into governance, strategy, and collaboration. Its eight helices create a coherent yet flexible structure that enables IZEs to align their dual transformation goals, mobilize capital, develop a future-ready workforce, and foster societal trust. The analysis highlights AHM's distinctive strength in its capacity for continuous adjustment. Unlike earlier helix models, it incorporates mechanisms for measurement, learning, and adaptive governance, making it particularly well-suited to navigate the uncertainties associated with digital transformation and ecological change. For policymakers, AHM serves as a blueprint for developing IZEs as dynamic platforms for sustainable economic growth. For practitioners, it offers a structured yet flexible toolkit to address implementation barriers. For academics, it opens avenues for empirical testing and refinement, particularly in assessing the long-term effects of adaptivity. Ultimately, by bridging the digital and green agendas through an adaptive, multi-stakeholder approach, AHM transcends theoretical frameworks to become a practical catalyst for building resilient, inclusive, and future-ready economies. Finally, AHM should be transformed from a theoretical concept into a practical reality. By this transformation, not only will its strengths be highlighted, but gaps and potential weaknesses can also be courageously confronted. Through the generation, analysis, and dissemination of real-world data, its true value and impact in the future can be unleashed.

11 Conflict of Interest Statement

The author, Saleh Alnouman, confidently affirms that no conflicts of interest are associated with this article's research, authorship, and publication.

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