

*Review*

Sustainability and Digital Innovation in the Integrated Risk Management

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Abstract: Growing complexity in environmental, technological, and regulatory domains has intensified the need for integrated risk governance aligned with sustainability objectives and ESG standards. Recognised increasingly as a strategic function, integrated risk management (IRM) supports long-term organisational resilience and value creation. This paper explores contemporary strategies that embed sustainability and digital innovation into IRM, including multi-criteria decision-making methods such as VIKOR, risk matrices incorporating resilience, ESG-based control systems, and simulation models suitable for uncertain environments. In comparing real and financial sectors, the analysis highlights distinct risk profiles, regulatory demands, and technological capacities. Particular attention is given to the contribution of artificial intelligence, big data analytics, and blockchain in enhancing adaptability and proactive decision-making. To assess digital maturity in risk functions, the S-curve transformation model is proposed as a conceptual tool. Rather than relying solely on analytical instruments, effective IRM also requires institutional readiness, continuous learning, and the integration of sustainability into strategic processes. Embedding these elements is essential for developing forward-looking, resilient systems of risk governance.

Keywords: *ESG integration; resilience metrics; multi-criteria decision-making; financial risk governance; S-curve model; digital maturity.*

1. Introduction

Modern business environments are increasingly shaped by complex and interconnected risks stemming from environmental, social, technological and geopolitical disruptions. In a climate of global uncertainty and heightened stakeholder expectations, organisations are recognising the need for more advanced and integrated risk management approaches that are closely aligned with sustainable development goals and ESG standards [1,2]. Moving beyond traditional, siloed practices, recent developments underscore the importance of cohesive frameworks that embed risk governance into long-term strategic planning and responsible corporate conduct.

Enterprise Risk Management (ERM) has evolved from an operational tool into a strategic mechanism for managing diverse risks, including those related to sustainability [3]. However, studies highlight limited integration of sustainability within traditional ERM frameworks, revealing a need for models that address data complexity, regulatory pressures and interdisciplinary insights

[1]. In addition, as digital transformation becomes a dominant force across sectors, the concept of digital maturity is gaining importance as a prerequisite for the effective implementation of risk governance systems. Together, these trends underscore the need for rethinking ERM not only in terms of sustainability alignment, but also through the lens of technological readiness and adaptive capacity.

In light of these challenges, there is a growing need to explore how various models can support the design of integrated and future-oriented approaches aligned with sustainability objectives. This paper analyses emerging strategies for embedding sustainability into risk management, with particular attention to multi-criteria prioritisation methods and innovations in managerial and governance structures.

2. Contemporary Approaches to Risk Governance for Sustainable Business

Risk management from a sustainability perspective involves embedding ESG criteria into all stages of risk identification, analysis, prioritisation, and control, with careful consideration of their potential long-term impacts on business operations, society, and the natural environment [4]. Unlike traditional approaches that primarily focused on financial risks, contemporary practices seek to develop integrated models that address a wider range of risks, including operational, regulatory, reputational, developmental, financial, environmental, and technological risks, and align them with the objectives of sustainable business.

Given the complexity of modern risk landscapes, it is crucial to clearly define the key categories of organisational risk that carry strategic relevance for sustainability. Accordingly, Table 1 outlines the core risk types, their specific features, and recent research contributions addressing each.

Table 1. Organisational risk categories relevant to sustainable business [4-15].

Risk type	Description
Operational risk	Involves internal failures, system errors, process weaknesses or human and information-related mistakes. Growing digital dependence and process complexity increase exposure, especially amid competitive and technological pressures. [5,6]
Regulatory risk	Results from non-compliance with legal requirements, including ESG standards. It may hinder alignment with evolving regulations and jeopardise long-term organisational sustainability. [4,7]
Reputational risk	Arises from how the organisation is perceived by key stakeholders. Reputational damage, particularly in ethical, social or environmental matters, can undermine market position, stakeholder confidence and financial outcomes. [8,9]
Developmental risk	Concerns the organisation's ability to adapt to external changes and sustain strategic growth. Poor adaptation to market or technological shifts may result in stagnation and loss of competitiveness. [10,11]
Financial risk	Relates to exposure to liquidity, solvency, capital access and market volatility. Misalignment with ESG standards can heighten these risks, while strong ESG performance and sustainable practices support greater financial stability and resilience. [10,12]
Environmental risk	Arises from the organisation's ecological impact and related obligations. Failure to comply with standards or prevent environmental harm may result in legal action and loss of stakeholder confidence. [11,13]
Technological risk	Stems from dependence on digital technologies and exposure to cyber threats, system disruptions and obsolescence. As digital systems become integral to operations, such vulnerabilities may compromise organisational resilience and continuity. [14,15]

To address this challenge, various models have been developed to support the identification, prioritisation, and quantification of sub-risks aligned with sustainable development principles.

These include multi-criteria decision-making methods, risk matrices with resilience elements, ESG-based systems, and logic or simulation tools for assessing risk under uncertainty. Each contributes to more effective integration of sustainability into organisational risk management.

2.1. Multi-Criteria Decision-Making Methods

Multi-criteria decision-making (MCDM) methods are recognised as a key tool in contemporary risk management under conditions of sustainable business. They enable the structured and quantitative assessment of complex decisions involving multiple, often conflicting, criteria, which makes them particularly suitable for analysing risks across environmental, social, and governance (ESG) dimensions. Among the various MCDM approaches, the VIKOR method—short for Multi-Criteria Optimisation and Compromise Solution—is especially notable for its ability to identify and prioritise sub-risks across a wide spectrum of domains, including geopolitical, economic, social, technological, and environmental areas. By balancing competing objectives, VIKOR generates compromise-based solutions derived from expert judgement and structured data inputs.

The broad applicability of the VIKOR method has been confirmed across a diverse set of sectors, such as manufacturing, supply chain management, energy systems, healthcare, education, and risk governance, thereby demonstrating its methodological flexibility and adaptability in both operational and strategic contexts [16]. In particular, its fuzzy logic extension has proven highly effective in assessing the health impacts of air pollution, illustrating the method's usefulness in shaping sustainable and preventive environmental health policies with long-term impact [17]. Furthermore, recent empirical research underscores VIKOR's practical value in prioritising organisational sub-risks and supporting the development of integrated risk management strategies aligned with the United Nations Sustainable Development Goals (SDGs) [18].

Compared with other MCDM techniques such as the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP), VIKOR is considered a robust and transparent approach. It allows clearly structured and compromise-oriented decision-making in situations of complexity and uncertainty, without the need to oversimplify decision criteria. This makes it highly appropriate for use in sustainability-driven governance systems where trade-offs among economic, environmental, and social priorities are common.

2.2. Extended Risk Matrices with a Resilience Component

Traditional risk matrices, based on a two-dimensional assessment of likelihood and impact, have long been a standard tool in organisational risk evaluation. However, in the face of increasingly frequent crises, heightened environmental volatility and growing demands for adaptability, such models often reveal important limitations. To better capture system vulnerabilities, extended matrices have been developed by introducing a third dimension: resilience. In this context, resilience refers to an organisation's ability to absorb adverse risk effects, maintain business continuity and recover rapidly from disruptions. These advanced matrices account not only for the probability and severity of impacts, but also for the system's capacity to respond, offering a more realistic and integrated perspective on complex risks within the framework of sustainability.

The inclusion of resilience as an additional criterion reshapes risk prioritisation and supports decision-making aligned with strategic objectives, particularly within the small and medium-sized enterprise (SME) sector [19]. A recent approach is reflected in a three-dimensional model that links probability, impact and the cost of risk management, allowing for a more accurate assessment of critical situations within organisations [20]. By incorporating budgetary constraints into the analysis, the focus shifts from probability alone to the cost-benefit ratio of risk reduction. This enables more efficient resource allocation towards priority risks and enhances overall organisational resilience. Nevertheless, the effective application of such a model requires adequate institutional capacity and clearly defined internal mechanisms for measuring resilience, which may pose challenges for less developed organisations.

Extended risk matrix models that incorporate resilience shift risk evaluation from static to a more holistic approach, supporting strategic planning under uncertainty. This improves organisational responsiveness and reinforces long-term stability and adaptability as key pillars of sustainable business. As risk complexity increases, especially in sustainability, there is a growing need to integrate ESG indicators into managerial control systems to align risk-related decisions with broader environmental, social and governance objectives.

2.3. Integration of ESG Indicators into Managerial Control Systems

The integration of sustainability into organisational decision-making requires a redefinition of existing managerial control systems (MCS) through the inclusion of environmental, social and governance (ESG) indicators. These indicators are becoming essential instruments for monitoring performance, steering strategic direction, and managing risks associated with non-compliance with sustainability principles. Unlike traditional control systems, which are primarily centred on financial metrics, modern MCS frameworks incorporate a broader set of factors that shape long-term value creation and strengthen organisational resilience.

Empirical studies confirm the growing integration of ESG indicators into both formal and informal managerial control mechanisms. For instance, research conducted among major Italian banking groups demonstrates that regulatory pressures, coupled with rising stakeholder expectations, have progressively driven the expansion and transformation of internal control systems. These developments have led to notable improvements in long-term strategic planning, administrative processes, incentive structures, and organisational culture, all aimed at embedding ESG objectives more systematically into daily management practices [21]. Similar findings are reported in the case of the Brazilian company Natura, which has adopted a comprehensive and structured approach by integrating sustainability principles and the goals of the 2030 Agenda into its internal control framework. This includes the development and application of new metrics such as Environmental Profit and Loss (EP&L), Social Profit and Loss (SP&L), and Integrated Profit and Loss (IP&L), which align non-financial performance indicators with strategic decision-making processes and risk assessment tools [22].

Such approaches highlight the transformative potential of MCS when embedded with ESG considerations. They not only allow organisations to monitor and quantify the sustainability of their operations, but also to identify risks and opportunities linked to sustainable development in a timely and structured manner. Nevertheless, implementation is not without its difficulties. Common challenges include the selection of appropriate and sector-relevant indicators, limited data availability, concerns over data reliability, and the interpretive variability of sustainability metrics across contexts. Despite these limitations, the available evidence suggests that ESG-integrated control systems can play a critical role in enabling the shift from transactional to transformational forms of management, thereby facilitating a more profound integration of sustainability into everyday organisational processes [23].

2.4. Simulation and Scenario Models for Risk Analysis

Simulation and scenario models are modern approaches to risk analysis, particularly suited to environments characterised by high uncertainty and complexity. These models enable the prediction of outcomes from various decisions across multiple potential scenarios, thereby enhancing strategic planning and strengthening organisational resilience. Simulation models focus on the quantitative analysis of variables that capture the dynamic nature of the business environment, while scenario models provide qualitative insights into possible future outcomes, often complemented by expert judgements. Although both approaches deal with uncertainty, simulation models typically rely on data-driven processes and numerical algorithms, whereas scenario models depend more heavily on narrative construction, expert elicitation and foresight techniques.

These models are especially valuable in systems with limited data availability and a large number of unknown variables. Recent studies have demonstrated the effectiveness of simulation models in assessing the sustainability of manufacturing processes under high uncertainty, using

methodologies that integrate logical frameworks with quantitative risk impact assessments [6]. Furthermore, in the context of urban planning, these models support the evaluation of environmental risks across various development scenarios, including the protection of natural resources and the assessment of long-term sustainability trade-offs between ecological preservation and urban growth objectives. In the financial sector, scenario analysis is increasingly used to evaluate the potential impacts of climate-related risks on asset portfolios, helping institutions prepare for regulatory stress testing and resilience reporting. Similarly, in disaster risk management, simulation tools are employed to model the spread of disruption across supply chains or infrastructure networks, allowing for more informed contingency planning. Despite their strengths, these models often require significant technical expertise, computational resources, and access to reliable data to ensure their validity and usefulness in real-world applications.

The application of simulation modelling has also been noted in revenue management within the real estate sector, where cash flow analysis and the identification of critical costs and revenues help define strategies for improving efficiency and reducing risk exposure [25]. Such models enable management to quantify the effects of uncertainty more accurately and to adapt strategies more effectively to changing business conditions. However, as simulation models are increasingly applied to multi-sector systems, particularly those addressing climate and economic shocks, researchers emphasise that these systems are often subject to deep uncertainties that limit the predictive and planning capacity of standard simulation approaches. Effective use of such models requires deliberate methodological choices throughout inference, scenario discovery and risk identification stages, supported by transparent communication, open access to modelling code and sensitivity testing across uncertainty dimensions [26].

3. Sectoral Differences in the Application of Integrated Risk Management and ESG Principles

The application of integrated risk management (IRM) differs significantly between the real and financial sectors, shaped by specific characteristics, regulations, risk exposure, and strategic focus. Key differences in approaches, priorities and ESG implications across these sectors are summarised in Table 2. In the real sector, which includes manufacturing, industry, agriculture and trade, IRM responds to the need for aligning operations with sustainability goals such as resource efficiency, environmental protection and climate resilience. Operational risks include supply chain disruptions, technical failures, human error, cyberattacks and regulatory changes, while ecological and reputational risks are becoming increasingly relevant due to public and institutional pressure [11,14]. In sectors such as energy and agriculture, IRM must address seasonal variability, natural disasters and CO₂ emissions, requiring adaptive and sector-specific strategies.

Table 2. Sectoral Differences in Risk Management Approaches.

Aspect	Real Sector	Financial Sector
Dominant Risks	Operational, ecological, technological, market	Credit, market, liquidity, reputational
IRM Focus	Physical protection, business continuity, supply chain resilience	Regulatory compliance, liquidity, portfolio stability
ESG Implications	Focus on environmental footprint, working conditions, community responsibility	Focus on transparency, ethical standards, and ESG integration in risk assessments
Technological Support	Sensors, IoT, digital twins for process monitoring	AI, Big Data, and predictive analytics for financial risk modelling
Sustainability in Practice	Eco-innovations, circular economy, production localisation	Green financial products, ESG reporting, sustainable investing
Challenges	High energy consumption, scarce resources, demand volatility	Regulatory complexity, investor pressure, reputational risk

The financial sector focuses primarily on credit, market, liquidity and regulatory risks, reflecting its exposure to financial volatility and the importance of maintaining compliance. It operates in an environment where market dynamics, liquidity and reputation are pivotal to systemic stability. Risk management in banks, insurance companies and investment funds involves sophisticated exposure assessment models and adherence to international standards such as Basel III, ESRS and the EU taxonomy [4]. Within this context, ESG factors are increasingly integrated into credit assessment, investment valuation and financial reporting processes, enabling financial institutions to meet the expectations of regulators, investors and the wider society [21].

Despite differing operational and regulatory frameworks, both sectors require a strategic approach to risk management that extends beyond short-term objectives. IRM aligns risks with ESG principles and sustainable development, enhancing resilience, competitiveness and transparency. This integrated approach supports informed decision-making by considering economic, social and environmental factors, which remains essential amid global uncertainty and structural transformation. As organisations pursue sustainability strategies, combining advanced technologies with the S-curve model in IRM will be key to addressing new risks and achieving lasting success.

4. Application of Technologies and S-Curve Transformation in Integrated Risk Management

Organisations are increasingly challenged by regulatory pressures, rapid technological change and complex risk landscapes. Within this context, digital technologies have become essential in integrated risk management (IRM), enhancing risk identification, quantification and monitoring, while transforming decision-making towards more predictive and adaptive approaches. Digitalising IRM involves the use of artificial intelligence, big data analytics, IoT, blockchain and automated algorithms, which enable dynamic risk mapping, scenario simulation and strategy development based on real-time data.

The application of digital solutions in IRM is both operationally and strategically significant. Predictive analytics help identify latent vulnerabilities not visible through traditional methods, while monitoring tools automate trend evaluation, detect anomalies and trigger early warnings. Research confirms that adopting Industry 4.0 technologies such as artificial intelligence, big data, cloud computing and blockchain enhances real-time risk management, especially in manufacturing [27]. The perceived value of these technologies, along with institutional and market pressures, is crucial for their integration into risk strategies. An organisation's digital maturity is also essential for effective implementation. It reflects the ability to align digital technologies with strategy, culture and operations, which is critical for sustaining long-term innovation and resilience. Recent bibliometric research confirms that digital maturity is a key enabler of sustainable digital transformation, particularly when sector-specific models are applied and adapted to industry needs [28].

In the financial sector, digital transformation improves efficiency and competitiveness but also introduces risks that require careful management. The digitalisation of banking has become a major source of operational risks, including increased transaction volumes, technological failures and security threats, despite rising cybersecurity investments [14]. Particular attention should be given to green banking, which incorporates ESG criteria into risk management and sustainable financial strategies. Risk management in this area not only protects banks from potential losses but also contributes to long-term socio-economic development and financial stability [29]. Recent research in the Serbian banking sector confirms that environmentally conscious clients are increasingly monitoring green initiatives by financial institutions, and that expanding green product portfolios can significantly enhance customer loyalty and sustainable value creation [30].

In addition to technological infrastructure and strategy, a critical element for the successful digital transformation of the IRM function is the development of organisational learning and innovation. Digital technologies enable the collection, processing, and exchange of knowledge, promoting the continuous adoption of new business practices and enhancing the organisation's adaptability. Empirical research confirms that digital transformation strengthens organisational resilience by improving their ability to learn and innovate, thus enabling quicker and more efficient responses to market shifts and systemic disruptions [31].

The S-curve transformation model provides a useful framework for understanding the evolution of digital IRM, identifying three stages of innovation: emergence, acceleration and stabilisation. It facilitates the assessment of an organisation's digital maturity and serves as a strategic tool for evaluating the adoption, performance and growth potential of new technologies. As shown in studies on digital signal processing, the model offers insights into the lifecycle and phased implementation of technologies, while also underscoring the practical challenges of its application in risk management under conditions of dynamic digital transformation [32].

5. Conclusions

Integrated risk management (IRM) is shifting from an operational necessity to a strategic framework that enables organisations to address challenges and enhance resilience. IRM aligns risk management with long-term goals, ESG principles and sustainable development. Multi-criteria decision-making methods support the prioritisation of sub-risks across sustainability dimensions, while extended risk matrices incorporate resilience in assessing vulnerabilities. The integration of ESG indicators into control systems improves monitoring. Technologies such as artificial intelligence, blockchain and predictive analytics enable dynamic risk identification and faster decisions, while the S-curve model provides a framework for understanding phases of digital transformation.

Sectoral differences highlight the need for tailored IRM models. The real sector faces operational, environmental and reputational risks, while the financial sector addresses market, credit and regulatory risks, increasingly relying on ESG criteria. Success depends on the organisation's ability to integrate risk management with innovation, learning and long-term strategy. Digital transformation of IRM involves adopting new tools, redefining managerial approaches, building organisational culture and developing adaptability in unstable conditions. Risk management becomes central to building resilience, value and sustainability.

Conflicts of Interest: The authors declares no conflict of interest.

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