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Integrating Sustainability and Digital Innovation: A Dual- Framework Approach for ESG Performance Assessment

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Abstract

In today's rapidly changing world, shaped by environmental, social, and technological challenges, sustainability has evolved from a marginal aspiration into a core requirement for long-term business continuity. In the meanwhile, digitalization is steadily reshaping organizational models, strategies, and operational processes, profoundly influencing how companies create and deliver value. Yet, despite their growing relevance, the intersection between these two forces remains largely underexplored, and companies struggle not only to assess their ESG performance but also to understand how digital solutions contribute to, or detract from, related goals.

To address such dual gap, this study proposes an integrated approach that connects sustainability assessment with digital transformation, leveraging on the development of two distinct yet interrelated tools. The first is an ESG framework, populated with over 200 KPIs and organized according to a carefully designed hierarchical structure, conceived to be applicable across sectors and industries. Providing a standardized and comprehensive representation of all sustainability dimensions, many of which to this day often overlooked, it offers a robust basis for consistent and comparable reporting, allowing organizations to select indicators aligned with their specific characteristics. Building on this foundation, the second developed tool is a multilayer causal model, uniquely designed to analyse the impact of digital solutions on sustainability in a structured and traceable way. Developed concurrently with its real-world application to Almagora's Smart Water Management project, and subsequently formalized in a schematic applicability guide, the model maps the pathways through which technologies generate ESG outcomes, by means of operational outputs and organizational drivers. The result is a clear and replicable structure that supports strategic decision-making and impact monitoring, ultimately facilitating the informed integration of digital innovation into corporate sustainability strategies.

Overall, this work aims to offer both a methodological and operational contribution to the debate on digital sustainability, providing practical and adaptable tools to support organizations on their path toward a more responsible, transparent, and long-term value-driven transformation.

Key-words: Sustainability, ESG, Digitalization, Framework, Causal Model, KPIs

Abstract in italiano

In un contesto globale sempre più complesso, segnato da sfide ambientali, sociali e tecnologiche, la sostenibilità è diventata una condizione imprescindibile per garantire resilienza nel lungo periodo, mentre la digitalizzazione sta inesorabilmente trasformando i modelli organizzativi e strategici delle imprese contemporanee. Tuttavia, nonostante la rilevanza crescente di entrambe le tematiche, l'intersezione tra sostenibilità e trasformazione digitale resta ancora marginalmente indagata, e molte entità faticano non solo a valutare sistematicamente le proprie performance ESG ma anche a comprendere il reale contributo che le tecnologie digitali hanno su di esse.

A fronte di queste sfide e difficoltà, apparentemente distinte ma in realtà profondamente connesse, il seguente studio propone un approccio bipartito, dove i temi della reportistica e del digitale vengono affrontati mediante lo sviluppo di strumenti complementari. Il primo è un framework ESG, popolato con oltre 200 KPIs e organizzato secondo un'attenta architettura gerarchica, sviluppato per garantire coerenza, standardizzazione e solidità nelle attività di misurazione e rendicontazione della sostenibilità. Ideato con l'obiettivo di essere applicabile indipendentemente dal settore o industria di appartenenza, il framework consente non solo di selezionare gli indicatori più coerenti con le specificità aziendali, ma anche di garantire una copertura completa e bilanciata di tutte le dimensioni di sostenibilità, delle quali molte, ad oggi, ancora trascurate. Il secondo strumento è un modello causale multilivello, progettato in forma originale per analizzare strutturalmente e in modo verificabile l'impatto delle soluzioni digitali sulla sostenibilità. Sviluppato in parallelo alla sua reale applicazione al progetto di Smart Water Management di Almaviva, e successivamente formalizzato in una guida applicativa, il modello ricostruisce i percorsi attraverso cui le tecnologie generano risultati ESG, passando per output operativi e driver aziendali. Il risultato è una struttura chiara e replicabile, utile per guidare le decisioni strategiche, monitorare gli impatti, e favorire un'integrazione più consapevole del digitale nelle strategie di sostenibilità aziendale.

Nel suo insieme, il lavoro mira a offrire un contributo metodologico e operativo al tema della sostenibilità digitale, fornendo strumenti pratici e adattabili per guidare le organizzazioni verso una trasformazione più responsabile e duratura.

Parole chiave: Sostenibilità, ESG, Digitalizzazione, Framework, Modello Causale, KPIs

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1 Introduction

1.1. A World in Transformation

In an era marked by unprecedented and deeply interwoven transformations, environmental degradation, technological disruption, geopolitical instability, and rising social inequalities are no longer separate or marginal issues. On the contrary, they are converging into a new global condition that challenges the very foundations of our development models.

For decades, under the assumption that natural systems could endlessly absorb human impact, economic growth was pursued with little regard for its social and ecological consequences, but, today, that assumption no longer holds [105]. The boundaries of our planet climatic stability, biodiversity, and freshwater availability are under intense pressure, and the ripple effects of this disruption are increasingly visible in everyday life, from extreme weather events and rising food insecurity to forced migrations and ecosystem collapse [2, 3].

As often happens, however, from this moment of crisis is urging the need for redefinition, and political institutions, civil society, and the private sector are all beginning to confront the reality that sustainability is not simply a goal to be pursued but a precondition for continuity. Inspired by what said by the economist Kate Raworth in her doughnut model [1], organizations around the world are slowly recognizing that true prosperity does not lie in indefinite expansion, but in the capacity to ensure human well-being while respecting the physical and social conditions that make life possible [1]. At the same time, scientific research has also shown that key Earth system processes, such as climate regulation, biodiversity maintenance, and nutrient cycles, have already been destabilized by human activity [2], reinforcing the urgency of rethinking the boundaries of our collective action. As a consequence, the need for a fundamental reassessment of how we define success, growth, and responsibility, not only at the institutional or governmental level, but within every decision that shapes the economy, society, and environment [7, 105]. Human activity has reached a scale at which it profoundly shapes the Earth system itself, and continuing on our current path risks irreversible damage.

1.2. Climate, Social, and Governance Instability

Among the many disruptions shaping our present and future, climate change stands out as the most urgent and far-reaching [2]. Once considered a distant environmental concern, it has now become a defining force in the global agenda, with impacts that extend across ecosystems, economies, and societies [4]. Scientific consensus is unequivocal in stating the planet is warming at an unprecedented rate [3], and human activity, primarily through the combustion of fossil fuels, land-use change, and industrial processes, is the dominant driver of this transformation [3].

Global surface temperatures have already risen by more than 1.2°C above pre-industrial levels, with the past eight years ranking as the warmest on record [4]. Worsening the situation even more, this phenomenon is not uniformly recognized but instead intensifies existing inequalities and vulnerabilities [3], with heatwaves, floods, and droughts becoming disproportionately more frequent and severe within the most exposed populations and regions [3]. Rising sea levels, driven by melting glaciers and thermal expansion, now threaten entire coastal communities, while changes in rainfall patterns disrupt food systems and freshwater availability on every continent [4].

Overlooking the fact that climate instability does not occur in isolation, but instead intersects with biodiversity loss, soil degradation, and socio-economic fragility [7], overall amplifying the risk of systemic collapse [69], emissions continue to rise. In 2023, global CO₂ concentrations surpassed 420 parts per million – the highest level in over two million years [5] – and current trajectories suggest that the 1.5°C threshold established by the Paris Agreement may be exceeded within the next decade without immediate and far-reaching action [5].

But environmental stress is only part of a wider sustainability crisis, as social inequalities too are widening both within and across countries, affecting income, access to healthcare, education, and basic services [8, 9]. According to the United Nations, more than 700 million people still live in extreme poverty, surviving on less than \$2.15 a day, while over 2 billion lack access to safely managed drinking water [6]. As of 2022, then, over 244 million children remain out of school, and nearly 1 in 3 people globally did not have access to adequate food [7, 8], overall determining the life expectancy of low-income nations to be 20 years shorter than in richest countries [9]. These conditions not only hinder human development but erode social cohesion and resilience, making societies more vulnerable to both climatic, economic, or geopolitical shocks.

At the same time, governance failures, such as corruption, lack of transparency, weak institutions, and irresponsible corporate behaviour, continue to undermine progress [12]. Within the corporate sphere, in fact, bad governance structures often lead to poor risk management, short-termism, and a lack of alignment between corporate actions and societal expectations, ultimately compromising both long-term value creation and the trust of key stakeholders [31]. Beside this, the global rise in misinformation, the

erosion of trust in public institutions, and the persistence of opaque decision-making processes challenge democratic accountability and the rule of law, exacerbating injustices and weakening the social fabric needed for inclusive, stable, and resilient societies [60].

1.3. Rethinking the Role of Business

In the face of escalating environmental threats, social fragmentation, and institutional fragility, the role of business is undergoing a profound redefinition, with companies not only evaluated through the lens of financial performance, but increasingly held accountable for their broader impact on society and the planet [16, 38]. This shift is not only ethical in nature but strategic, as organizations that ignore environmental degradation, exploitative practices, or governance failures risk losing legitimacy, investor confidence, and their long-term license to operate [31].

This evolution becomes even more significant if considering the recent-growing momentum toward stakeholder capitalism [16], according to which businesses are no longer expected to serve only shareholders, but to create value for a wider ecosystem of actors, including employees, customers, communities, regulators, and future generations [31, 49]. It is not by chance, in fact, if leading international initiatives, from the UN Global Compact to the World Economic Forum's Davos Manifesto, now promote a model of corporate responsibility that emphasizes sustainability, inclusiveness, and transparency as integral to long-term success [60, 105].

Another fundamental driver of such transformation is the market, with consumers increasingly making purchasing decisions based on ethical and environmental considerations rather than focusing only on economic convenience [108]. Employees, particularly younger generations, prefer to work for companies that align with their values, investors are integrating ESG factors into risk assessment and portfolio management, and capital is flowing toward firms that demonstrate resilience and responsibility, not only profitability [10, 31]. A turning point in this conversation came in 2018, when Larry Fink, CEO of BlackRock, the world's largest asset manager, declared in his annual letter to CEOs that "every company must not only deliver financial performance, but also show how it makes a positive contribution to society" [10]. In the years since, his messages have grown sharper, stating that sustainability is the "new standard for investing" and warning that companies ignoring environmental and social risks will face capital reallocation. According to Bloomberg, global ESG assets under management surpassed \$40 trillion, signalling a decisive shift in how value is defined and measured in the financial world [11].

At the same time, regulatory pressure is mounting, with new frameworks such as the EU Corporate Sustainability Reporting Directive (CSRD) and the Sustainable Finance

Disclosure Regulation (SFDR) raising the bar for transparency and standardization [12, 13]. Companies are being pushed to move beyond generic sustainability narratives and demonstrate how their strategies align with national and international climate goals, social obligations, and governance expectations, providing not only strong verbal promises but concrete data and results [50, 103].

This new era calls for businesses to act not only as economic actors but also system wardens, as it is now acknowledged that their choices about resource use, employment practices, innovation, and supply chain management have far-reaching consequences [38]. As such, sustainability can no longer be treated as a peripheral function but must be embedded into the core strategy, governance structures, and day-to-day operations of every organization [31].

1.4. The Promise and Risks of Digitalization

As businesses are called to operate more sustainably, they must also navigate the parallel and equally transformative shift brought by digitalization [44]. Emerging technologies such as artificial intelligence, big data analytics, the Internet of Things, and blockchain are radically reshaping how organizations produce, manage, and communicate value, and what was once considered the domain of IT departments is now central to every strategy, operations, and governance [21, 83].

In this context, digitalization is not merely a backdrop to sustainability but a powerful lever for change, able to offer unprecedented opportunities for measuring environmental impact, monitoring real-time performance, optimizing resource use, and enhancing transparency [37]. From remote sensing technologies to automated reporting systems, innovation is enabling a more precise and scalable approach to sustainability, while also reinforcing accountability. Indeed, by helping organizations track progress and communicate their efforts credibly to stakeholders [37, 44], digital transformation emerges as not only compatible with sustainability but essential to achieving it [88].

However, digitalization is not inherently sustainable, and organizations are increasingly coming to terms with the reality that the rapid expansion of data infrastructure comes with growing energy demands, electronic waste, and questions about data ethics, inclusion, and cybersecurity [14, 59, 192]. Just to mention a few, data centres alone accounted for 4% of U.S. electricity consumption in 2023 and generated over 105 million tonnes of CO₂ equivalent [14], while global e-waste reached a record 62 million tonnes in 2022, with only about 22.3% formally recycled [15]. Without intentional governance, therefore, it appears evident that the same technologies that can support sustainability may also reinforce inequalities, consume critical resources, or introduce new risks [60].

In this complex and fast-changing context, understanding the interaction between digital transformation and sustainability is therefore essential, not only for identifying new opportunities and managing emerging threats, but also for shaping strategies that are resilient, inclusive, and aligned with long-term societal and environmental goals [44]. For companies, this means embedding digital innovation within a broader strategy that is not only efficient and competitive, but also ethical, inclusive, and environmentally responsible [54, 89].

1.5. Thesis Objectives, Methodology, and Structure

In such context, where the convergence between sustainability and digitalization emerges as both a necessity and an opportunity, it becomes essential not only to understand these phenomena in isolation, but also to investigate how they can be jointly addressed through structured tools and actionable strategies.

Acknowledging the dual challenge confronting companies, urged to strengthen their ESG performance while trying to understand how digital solutions can contribute to, or compromise, this objective, the present research aims to offer a comprehensive and operational response by developing two integrated instruments. The first is an ESG assessment framework, introduced to respond to the lack of coherence, comparability, and coverage that characterizes current sustainability reporting practices. Conceived as a structured and hierarchically organized tool, comprehensive of over 200 KPIs, it is designed to help companies identifying, standardizing, and monitoring sustainability indicators, enabling them to assess their sustainability practices in a coherent, comparable, and customizable manner. Building on this foundation, the second part is structured around the definition and introduction of a multilayer causal model, designed to trace the pathways through which digital technologies influence sustainability outcomes and overall assess their impact on ESG performance. Applied to a real-world case in the field of Smart Water Management projects, the model links enabling technologies to ESG impacts through intermediate operational and organizational variables, offering a structured, transparent, and replicable method for assessing digital sustainability effects.

Methodologically, the thesis combines different techniques, tailored to the specific requirements of each section's objectives. The first part, focused on the development of the ESG framework, relies on an extensive review and classification of over 80 academic papers, complemented by regulatory sources (such as ESRS and SDGs) and corporate sustainability reports. KPIs are collected, categorized, refined, and structured through a hierarchical system, with precise attribution of formulas and metrics to ensure coherence, comparability, and practical applicability. The second part, instead, sees the development of the above-mentioned causal model as an original contribution, conceived in response to the absence of existing methodologies

capable of explicitly tracing the impact of different variables on final outcomes in a structured and operational way. Constructed contextually to a real-world application, the overall novel structure of the model finds its roots in the review of a wide range of modelling approaches, drawing selectively from theory-based models, system dynamics, causal mapping, and evaluation frameworks. While no existing methodology was found to fully meet the analytical needs of the study, many of the model's individual components can be conceptually traced back to these established traditions, ensuring both academic robustness and analytical legitimacy. Progressively refined and validated through direct engagement with stakeholders, the model is ultimately generalized through a formalized application procedure that enables its scalability across different industries, projects, and digital technologies, demonstrating its potential as a practical decision-support tool for future practitioners.

To guide the reader, the thesis is organized into ten major sections, with Chapter 2 initially presenting an extensive literature review covering both sustainability assessment practices and modelling approaches relevant to digital-ESG interactions. Chapter 3 introduces the research questions and illustrates the overall methodological strategy adopted throughout the study, while Chapter 4 describes the process undertaken to formally structure and populate the ESG framework, detailing its hierarchical organization and indicator selection. Moving to the second focus area, Chapter 5 provides context for the selected project and the company of reference, Chapters 6 and 7 are dedicated to the design and application of the multilayer causal model, and Chapter 8 ultimately addresses the model's scalability by formalizing a generalizable procedure for broader application. Finally, Chapters 9 and 10 offer a critical discussion of the results, highlight the theoretical and practical contributions of the study, and outline potential directions for future research.

2 Literature Review

To provide a solid foundation for the research, this chapter presents a structured review of the existing literature at the intersection of sustainability assessment and digital transformation, articulating it into two complementary parts.

The first section (Chapter 2.1.) adopts a contextual and content-oriented perspective, aimed at mapping the landscape of sustainability assessment practices across corporate and institutional domains. It reviews the evolution of ESG thinking in business strategy, the development of regulatory and reporting frameworks, the diffusion of sustainability KPIs, and the emerging contribution of digital technologies to sustainability monitoring and performance. The underlying aim is to provide a critical overview of what is being measured, by whom, and with what limitations, highlighting the fragmentation, heterogeneity, and practical constraints that justify the need for more coherent ESG assessment frameworks.

The second part (Chapter 2.2) shifts instead the analytical lens from descriptive content to methodological structure, exploring how these phenomena have been conceptualized and modelled throughout years. This section delves into the modelling approaches used to map causal relationships and systemic interactions, especially in contexts where digital tools are leveraged to enhance sustainability outcomes. It classifies and compares twelve modelling approaches grouped into four methodological families, critically assessing their capacity to address complexity, interdependencies, and decision-making in ESG evaluation. The final objective is in this case not only to identify modelling strategies that can inform the construction of the thesis's original model but also to support its methodological design through the recognition of transferable logics and limitations.

Together, these two perspectives, contextual and methodological, address both the *what* and the *how* of the research domain, helping not only to consolidate current knowledge, but also to clarify the methodological and practical gaps that motivate the thesis' main contributions.

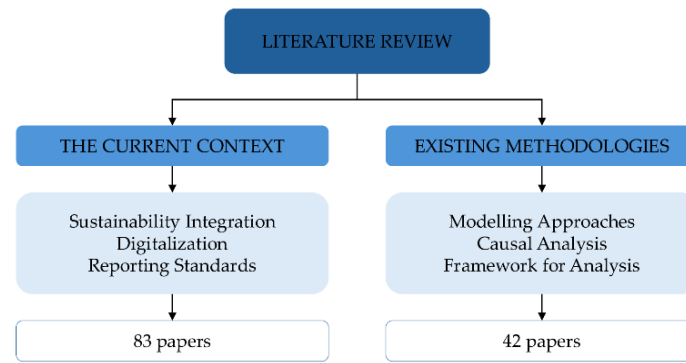


Figure 1: Literature Review Schematization

2.1. The Context

2.1.1. Introduction

The exploration of existing literature represents a fundamental and critical step in the research process, allowing to gain a deep understanding of the current knowledge concerning the selected topic and giving the possibility to identify gaps that still need to be addressed.

In recent years, due to the always more concerning environmental issues and targets set by corporations worldwide, the integration of sustainability practices in business operations has gained significant attention [38]. Companies are called to actively contribute to the achievement of aforementioned goals, and consequently strive to balance economic success with environmental and social responsibilities, trying to lead the change toward a more conscious way of operating. Fundamentally, the concept of sustainability in business has evolved from a mere environmental concern to the need of developing a successful strategy able to encompass both economic, social, and environmental aspects [16]. However, despite the increasing attention given to this topic, companies still face challenges in monitoring the impact of their activities, and struggle with the absence of precise and exhaustive guidelines for how to disclose the related information.

From the second half of last century, digitalization has started to emerge as a transformative force able to lead companies toward more efficient performances, and its integration in business models has become always more substantial. Despite initial doubts regarding the possibility for digital tools to improve the environmental impact of corporates' daily operations [99], it is nowadays recognized the fundamental role that new information technologies have in achieving sustainable targets [52, 62, 75, 85, 95, 96, 99], and organizations try to leverage on their potentialities.

In this challenging and complex context, the following literature review aims to scrutinize released articles and papers that concentrate on the dual themes of sustainability assessment and digitalization to present an overview of recent findings and gaps for improvement. Focusing either on the proposal of new sets of KPIs, the elaboration of analytical models that lead to single sustainability indexes, or the assessment of digitalization over organizational performance, these studies provide comprehensive insights into the world of sustainability assessment, leaving the possibility for future researchers to find interesting gaps for the development of new strategies and methods. Through this analysis, the review seeks to chart the evolution of sustainability assessments over time, highlight the role of digital technologies in enhancing these valuations, and explore the integration of real-time data into sustainability practices.

2.1.2. Collection Method

For this literature review, collection of papers was primarily conducted using Scopus database, which allows the specification of topics and key words to be included in the research and therefore guarantees a focused and case-specific selection. Additionally, the search was complemented by supplementary documents from authoritative sources such as United Nations and EU, which were crucial for providing a deeper understanding of the context and a broader consideration of standards and regulations currently in place.

2.1.2.1. Keywords and Initial Screening

To ensure a thorough exploration of the topic, a variety of keyword combinations were attempted, applying the results on both the abstract and the main body of the papers. As shown in the following analysis, tried matches ranged widely, including terms such as “Assessment”, “KPIs”, “Data”, and “Digitalization”, always coupled with the underlying concept of “Sustainability”, which remained specified for all queries. This strategic variation in keywords aimed at covering both broad aspects and specific intersections of sustainability assessment and digital technology’s introduction in business contexts, defining the borders of the study.

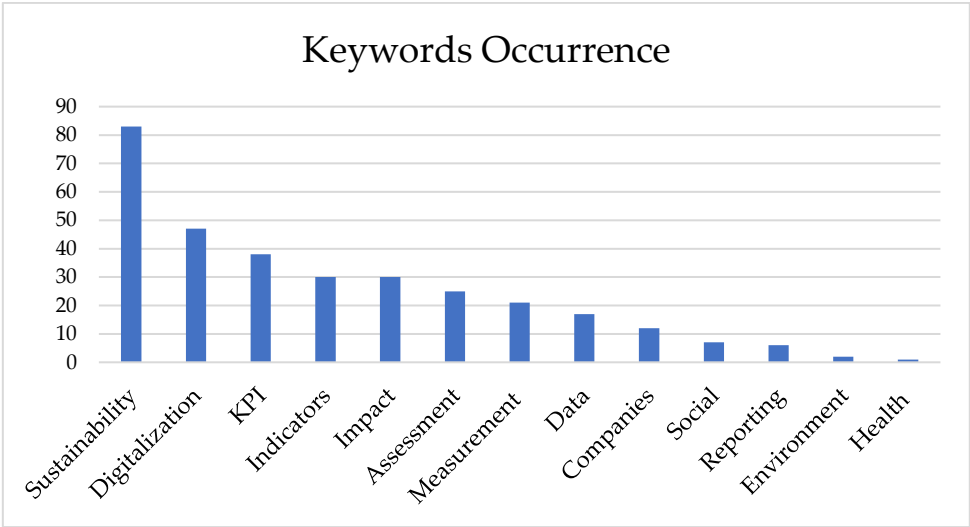


Figure 2: Keywords Occurrence in Papers Search

In total, 103 documents were initially identified, but a first selection was applied to account for the credibility and relevance of the work and focusing only on articles published in official journals. As a result, all non-conforming material was discharged, including conference papers, book chapters, and other non-peer-reviewed publications. Of the 85 finally collected papers, only three were impossible to download, either integrally or in English language, therefore reducing the number of analysable documents to 83.

2.1.2.2. Search Period

No limitations were applied in terms of publication period, as the goal was to include all relevant contributions independently from the date of their writing. This inclusive approach was first chosen to avoid any bias but also to potentially capture pioneering works from earlier years that may have shaped later developments in sustainability assessment and the role of digital technologies.

At the same time, the increasing urgency of sustainability issues and the rapid advancement of digital tools made it evident from the outset that the most methodologically robust and contextually relevant studies would likely come from more recent years. Keeping the timeframe open thus allowed the search strategy to naturally reflect the dynamism and temporal acceleration of academic and corporate interest in this interdisciplinary domain, without distorting or artificially guiding the results.

2.1.3. Papers Classification

2.1.3.1. Year of Publication

Although no specific time restrictions were imposed during the search, no document was found older than 2010, and a notable intensification in publications is evident from 2020 onwards. This surge is particularly prominent, with the last five years collectively accounting for 73 out of the 83 documents reviewed, which corresponds to approximately 88% of the total.

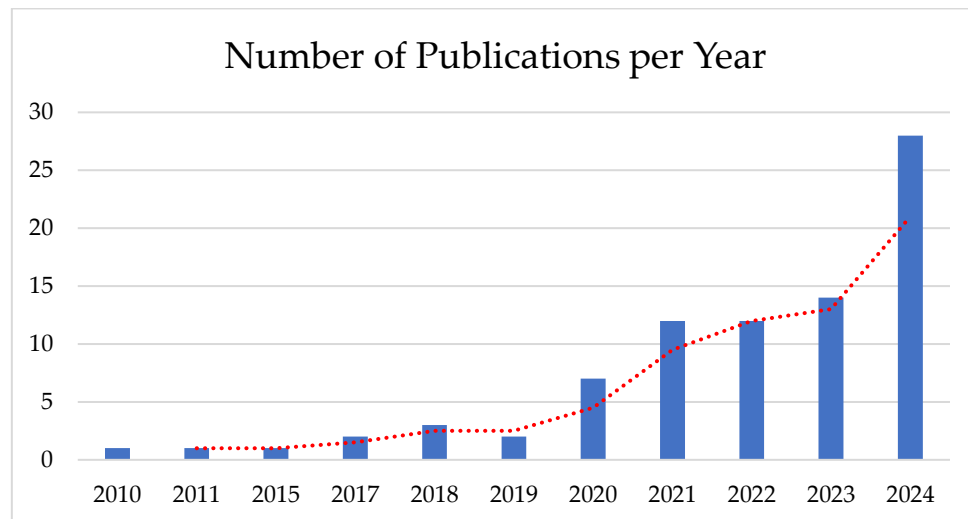


Figure 3: Distribution of Reviewed Papers by Year of Publication

This increasing number of publications clearly reflects the growing importance given to sustainability overall, and digitalization as a consequence, in the corporate sector in recent years. Indeed, the steep rise in literature from 2020 onwards not only aligns with the rapid advancements in digital tools and ICT, but also correlates with the increased implementation of sustainability regulations and corporate responsibility standards globally, as for example the 2015 Paris Agreement, which set ambitious climate change objectives for its signatories. Moreover, the COVID-19 pandemic too represented a notable responsible factor, as it highlighted the necessity for businesses to operate sustainably and leverage technologies for increased resilience and efficiency. This period saw in fact a rapid and consistent adoption of digital tools and sparked increased academic and industry interest in exploring and documenting the convergence of sustainability and digitalization.

As companies are urged to comply with more stringent environmental laws and as consumers increasingly demand sustainable practices, the relevance of this research area is likely to continue growing. Looking ahead, it is in fact reasonable to predict that this trend will not only continue but potentially accelerate, seeing an intensification of publications related to the topic. As more nations commit to carbon neutrality, the number of studies aimed at defining a clearer framework for sustainability assessment

is going to increase, and the advent of newer technologies, such as AI and big data analytics, that have the potentiality to monitor progresses in real time, will only expand the interest further.

As a matter of fact, the increasing number of publications noticed in the last decade serves as a testament to the growing relevance of the intersection of sustainability and digitalization in current and future business environments, acting as a foundation for future research.

2.1.3.2. Country

The geographic distribution of papers included in this literature review spans a wide array of countries, spread across different continents but majorly concentrated in the European region. The 83 analysed papers belong in fact to all the five continents, but the distribution is not homogeneous and a great discrepancy can be recognized between the two major contributors, Europe and Asia, and the rest of the world. The two leaders, in fact, published together more than 90% of the total number of papers, demonstrating their intense work toward the definition of more comprehensive sustainability assessment methods and the analysis of digitalization's impact on the proposed solutions.

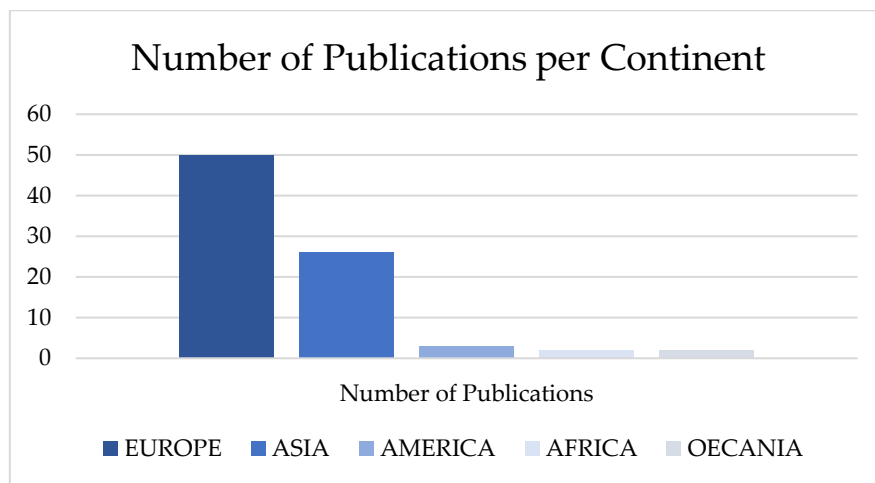


Figure 4: Distribution of Reviewed Papers by Continent

Europe

Interestingly but not surprisingly, almost all European countries have contributed with at least one publication to the literature on sustainability assessment and the role of digitalization on its improvement, giving evidence of the EU's proactive stance on environmental issues. The union has in fact been at the forefront of implementing new regulations and setting ambitious targets for sustainability, therefore encouraging member nations to take action toward a smoother transition to a climate friendly

economy. The Green Deal initiative, for example, encompasses a broad range of policy areas to make Europe the first climate-neutral continent by 2050, setting the target for companies for a more responsible behaviour. Additionally, the EU's focus on digital integration across its member states enhances research interest even more, leaving space for the creation of a fertile ground where academics can explore practical applications, assess policy impacts, and develop new methodologies.

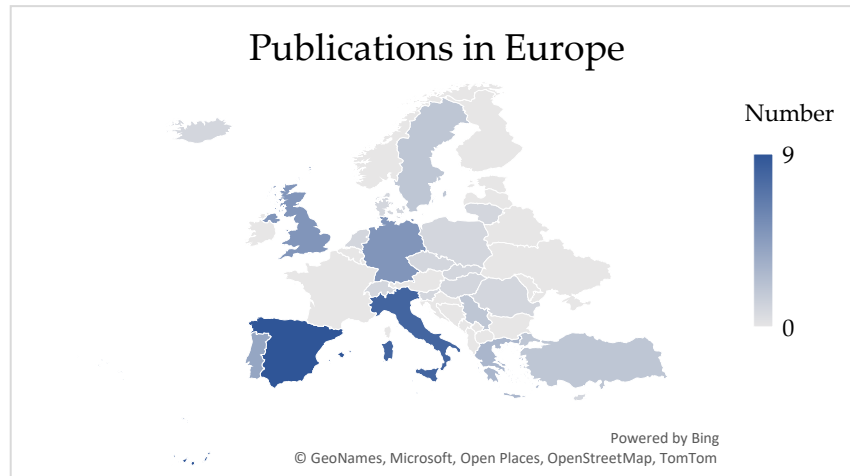


Figure 5: Distribution of Reviewed Papers by Country – European Continent

Asia

On the other hand, Asia as well gave evidence of great interest in the research topic, being responsible for the publication of around 30% of the total selected output. In this regard, it is notable that, while some of these papers focused on the elaboration of new sets of KPIs that companies can use to improve their reporting, a consistent half of them fixed instead on the assessment of digitalization's impact over corporate sustainability. This focus underscores the region's unique position as a rapidly growing economic region with significant technological advancements and industrial expansion. Hubs like China, South Korea, and India are in fact at the forefront of digital innovations, and their contribution to AI, IoT, and big data analytics are reshaping various industries, prompting extensive academic research into how these technologies can enhance sustainability efforts.



Figure 6: Distribution of Reviewed Papers by Country – Asian Continent

2.1.3.3. Adopted Methodology

In exploring the diverse methodologies employed across the literature, a wide range of research approaches could be observed, reflecting the multifaced nature of the field. However, it is important to acknowledge that, even if each paper has been classified according to its primary methodology, many of them actually adopted a mixed methods approach that led to the integration of multiple techniques. The combination of surveys, case studies, and quantitative analysis was not rare within the same study, and is indicative of the complex nature of the research topic, which often needs the intersection of different techniques to reach a more comprehensive and nuanced understanding of the issue.

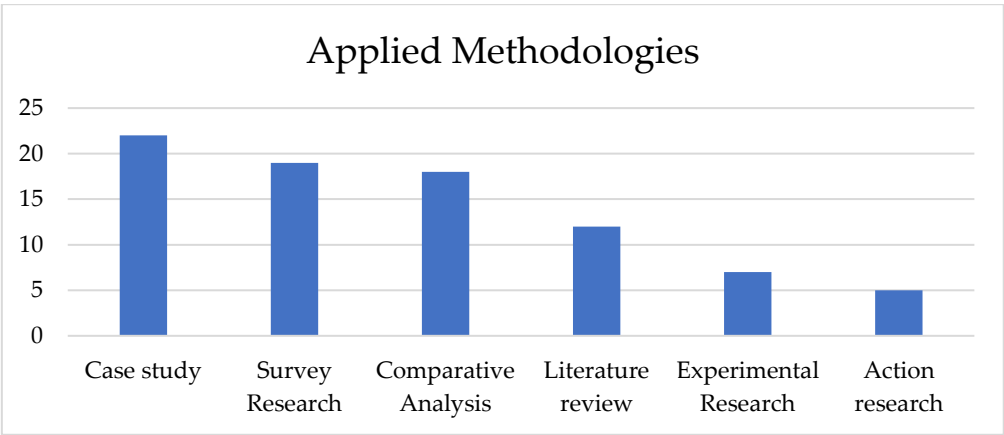


Figure 7: Distribution of Reviewed Papers by Applied Methodology

As shown in the chart above, the most common methodology, adopted in 22 papers, involved in-depth case studies, carried out on either single companies or entire nations. Being either descriptive, explanatory, or exploratory, these real-world

applications allow authors to explore complex contexts providing detailed insights into the specific processes, outcomes, and challenges encountered. Papers employing this methodology typically focused on individual organizations, projects, or contexts, extracting lessons and insights that could be generalized to other similar settings. In some cases, for example, the goal was to create a tailored model that could perfectly fit the selected subject, giving also a practical representation of how reasoning should be carried out when dealing with complex topics such as sustainability assessment. For instance, Larrinaga et al. [22] designed an integrated smart city services framework specifically for the city of Vitoria-Gasteiz, in Spain, adapting its structure to local governance and infrastructure needs, while Argente García et al. [76] developed a digital governance model for water resources management in Mediterranean agriculture, customizing it to address regional environmental and operational challenges. In other cases, instead, a company or sample was used to test the applicability of the previously developed model and to demonstrate either its suitability for the specific chosen context or its generalizability to different industries. In this regard, De Sanctis et al. [45] applied the MIKADO smart city KPI framework to selected municipalities to validate its robustness in real-world settings, while Contini et al. [88] validated a previously developed KPI system customized for the ceramic industry through direct application in partner companies. In both circumstances, however, authors provided great evidence of the solution's implementability, helping to clarify how selected indicators should be applied, targets set, and results communicated.

The second most utilized methodology was based on the collection of quantitative data from large groups of subjects through the distribution of questionnaires and structured surveys. Particularly helpful to gain insights about behaviours, attitudes, and concerns related to themes of sustainability assessment and digitalization's impact, this approach allows to take into consideration the perspective of stakeholders and elaborate theories and conclusions based on them. In many cases, in fact, the large amounts of collected data were used in combination with a quantitative analysis to statistically evaluate the impact of success factors and the relationship between variables. Examples are Karpuz et al. [65], who developed and validated a sustainable-performance instrument for the Northern Cyprus banking sector using survey responses from industry professionals, and Okfalisa et al. [66], who assessed SME readiness for digitalization through a multi-perspective survey, applying statistical models to examine factor relationships.

Comparative analysis was then adopted in 18 articles, with the goal to identify trends, compare groups, and establish relationships among variables across different contexts or conditions. In this case, data from multiple countries or cities were used to analyse trends and impacts on a global scale, establishing potential causations between various factors and the quality of performances. For instance, Han et al. [84] investigated the asymmetric effects of eco-digitalization on environmental sustainability in the USA,

while Haller et al. [77] examined the interplay between economic growth, digitalisation, and renewable energy adoption across European nations. Leveraging on econometric models like Generalized Method of Moments (GMM) [79] or the Panel Vector Auto-Regression (PVAR) [75], these papers mainly aimed at understanding patterns and effects across a wide spectrum of subjects and not at delving deep into specific of particular situations, organizations, or communities, as it instead typically happens in case studies.

Employed in 12 papers, the literature review approach was mainly used in those cases where the goal was to synthesize existing research findings to provide an overview of current knowledge and identify prevailing trends and gaps within the field of sustainability and digitalization. Valuable examples of this kind are Guandalini [99], who conducted a systematic review on sustainability through digital transformation, and Gazzola et al. [70], who performed a bibliometric analysis on the evolution of “digitainability” in the fashion industry. While this kind of studies does not typically progress beyond the current findings, its comprehensive analysis contributes significantly to the academic dialogue, offering a distilled perspective on the accumulated research and setting the stage for future inquiries. It is not a case, in fact, that all 83 selected papers began their research with a literature review, which is indeed essential for framing the research questions, helping in hypothesis formulation, and justifying the need for new or improved models and solutions.

Seven articles were then classified as experimental papers, as they developed analytical and assessment models without practically testing on real world use cases but basing on existing literature and personal reasoning. For example, Perroni et al. [18] proposed an experimental framework to analyse the dynamic equilibrium of sustainable ecosystem variables, while Hasan et al. [55] designed a blockchain-based sustainability index score entirely from conceptual foundations before field implementation. While these models are grounded in robust academic research to identify successful strategies and common pitfalls, they hypothesize about the potential effectiveness and applicability of results, leaving space for future developments and testing. This approach facilitates a deeper understanding of the underlying principles and variables that drive sustainability in a digital context, setting a theoretical baseline from which practical applications and future studies can evolve.

Finally, 5 papers were developed in the form of action research, involving a participatory approach where researchers worked collaboratively with participants to solve practical problems and contribute to scientific knowledge. This approach, which typically involves the direct engagement of stakeholders through face-to-face interviews and workshops, often proves essential in iteratively refining solutions through cycles of testing, reflection, and adjustment. Collaboration is indeed invaluable for uncovering nuanced insights that traditional surveys may not capture, and this becomes particularly evident in the view of complex topics, such as

sustainability assessment, that often need coordinate brainstorming to be properly explored and addressed. Walkiewicz et al. [31], for example, worked directly with corporate stakeholders to embed sustainability and externalities into organizational practices, while Argente García et al. [76] engaged agricultural and governance actors in the Mediterranean to co-design digital water management solutions.

2.1.3.4. Purpose

Referring to the main goal or objective that the research aims to achieve, the purpose of a study fundamentally defines what the authors intend to discover, demonstrate, or develop through their work. It helps to guide the study design, the choice of the methodology, and the analysis of results, ensuring that the elaboration remains focused and relevant to its intended outcome.

The outputs of selected papers, as shown in the chart below, demonstrate a diverse range of contributions to the field of sustainability assessment and digitalization, going from reporting frameworks and guidelines' development to the creation of models for understanding the impact of variables on results.

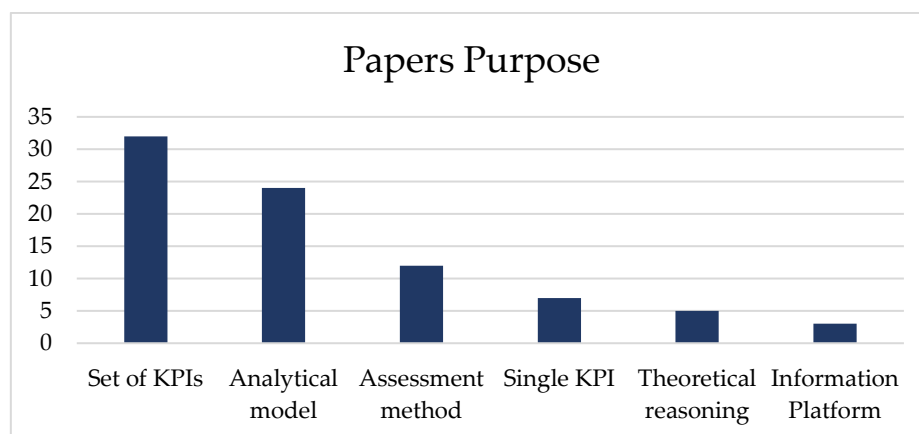


Figure 8: Distribution of Reviewed Papers by Purpose

The most common output among the reviewed papers is the development of a set of Key Performance Indicators (KPIs), designed to help organizations measure and manage their performance effectively. This focus on indicators demonstrates a strong interest in providing actionable measures that companies can implement to track and improve their environmental and social impacts, and is a proof of experts' attempt to provide clearer guidance for an effective reporting. For instance, Amaro et al. [27] proposed a detailed KPI framework for waste control in the catering industry, while Dasallas et al. [39] developed technical KPIs for Smart Water Cities aligned with global certification schemes. Among these sets, many are focused on specific industries and designed with the aim to fill the gap in current policies, offering practical help for managers working in sectors for which there is no official definition of best practices.

yet. For instance, Goti et al. [28] developed manufacturing audit KPIs to address sustainability shortcomings, while Gualeni & Maggioncalda [29] proposed indicators for ship performance. Yet, although the Global Reporting Initiative (GRI) already sets the standard for majorly important industries, such as Oil and Gas, Agriculture, and Mining, many others are still uncovered and need further investigation.

Another significant percentage of papers aims at analysing the impact of certain variables, such as technologies and digital tools, on sustainability outcomes, as in the case of Wang et al. [53], who empirically assessed how digital transformation influences corporate sustainability in the sports industry, or Jiang et al. [73], who explored the role of supply chain digitalization in reducing emissions in the natural resources sector. The goal is in this case to demonstrate the major help that digitalization can provide to companies for improving and monitoring their sustainability levels, as well as for reaching the SDGs targets. Many studies carried out in the form of comparative analysis, in fact, aimed understanding the causal impacts of technology implementations, policy changes, or other interventions on predefined indicators like economic growth, environmental sustainability, or social structures.

Framework evaluation models were instead developed in the case authors' goal was to assess, critique, and potentially improve existing dashboards and measures, as in the case of Ojo et al. [23], who examined technology integration in food manufacturing supply chains, and Kamišalić et al. [67], who evaluated the sustainability of natural fiber-based value chains in SMEs through digitalization-focused frameworks. This output category includes papers that evaluated the effectiveness, applicability, or comprehensiveness of theoretical models, and suggested enhancements based on empirical evidence. Instead of proposing new assessment methodologies, these studies mainly examined the robustness of already implemented ones and evaluated the adequacy, efficiency, and effectiveness of different approaches to manage sustainability in corporate or policy settings.

Similar to the first case, a still considerable number of papers aimed instead at developing a new, original index for quantify and simplify the assessment of performance. Examples are the ChemESI index introduced by Plugge [26] to standardize environmental metrics in the chemical sector, or the blockchain-based sustainability index score designed by Hasan et al. [55] for consumable products. In all these cases, the goal was to provide a clear, overall measure of sustainability that could be easy for stakeholders to understand, communicate, and utilize, suitable to track and compare results across different entities or time periods.

Some papers, majorly classified as literature reviews of exiting notions, focused on an extensive and structured examination of all relevant studies with the aim of integrating findings and providing a holistic view of the field [60, 64]. Through a deep identification of recurrent themes, influential works, and interrelation between

variables, authors of these studies mainly aimed at consolidating knowledge and guiding future academic research based on recognized gaps.

Finally, a total of 3 studies went beyond the mere definition of KPIs and provided an informational application or set of tools designed to assist businesses or organizations in making informed, data-driven decisions. These systems typically integrate various type of data, from KPIs to impact analyses, to provide help in evaluating options, predicting outcomes, and making strategic choices effectively, relying on real-data communication. Pragmatic example is in this case the work of Argente García et al. [76], who developed a digital governance platform for Mediterranean agriculture, able to integrate KPIs, environmental impact assessments, and stakeholder input to support strategic water management decisions.

2.1.3.5. Field of Application

The papers analysed within this literature review span a diverse array of industries, reflecting the importance of sustainability assessment and digitalization themes across different sectors.

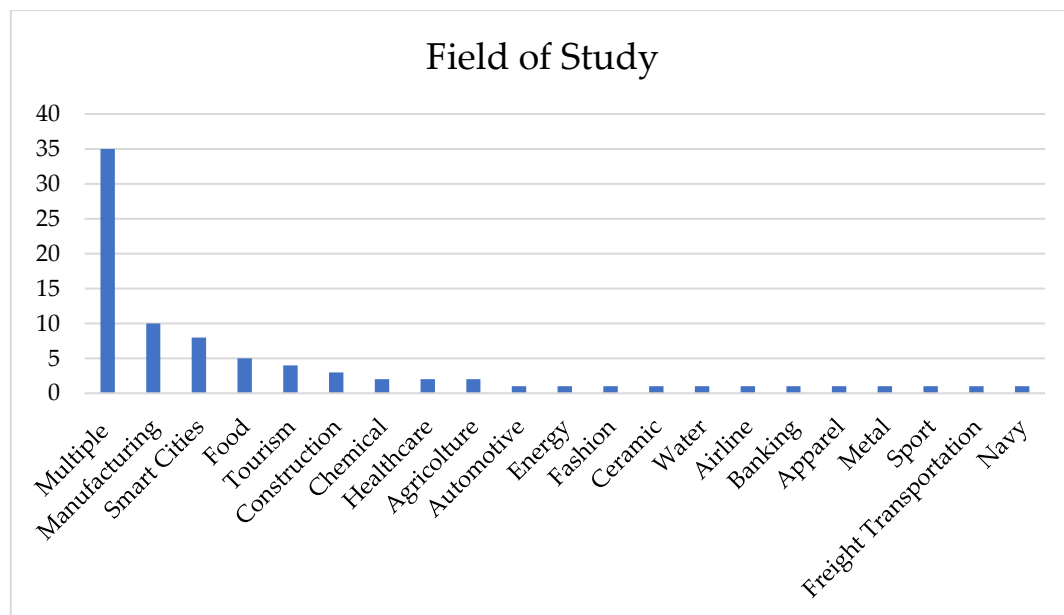


Figure 9: Distribution of Reviewed Papers by Field of Study

A considerable number of studies did not target any specific industry but instead focused on developing analytical models, or evaluating the state of the art in sustainability practices, that are applicable across multiple fields. This overarching perspective is particularly beneficial for the research, as it underscores the universal relevance and adaptability of chosen concepts irrespectively of the industry context.

Among specific industries addressed, manufacturing was the most frequently discussed, with 10 papers exploring its unique sustainability challenges and opportunities for digital enhancement. Smart cities as well represented a significantly analysed field, with a total of 8 papers dedicated to assessing how digital technologies can be used for urban sustainability improvement and what sets of KPIs should be implemented to better track their impact on the environment. Food, tourism, and construction industries were also notably represented, each addressed in several papers that highlighted their specific environmental and operational challenges.

Diverse other industries were explored in the collected articles, ranging from fashion and apparel to transportation and energy. This diversity in industry coverage, although less frequent in occurrence, enriches the research landscape by providing insights into the unique challenges and opportunities specific to each sector. Moreover, the inclusion of these varied industries demonstrates the expansive scope of sustainability and digitalization research, highlighting that these concepts are not confined to traditionally high impact sectors but are relevant across a wide spectrum of fields. At the same time, however, the fact that many papers focused specifically on certain industries underscores the tendency to develop solutions, models, and frameworks implementable in well-defined contexts, and not to organizations overall. Indeed, while sector-specific studies provide valuable insights into tailored sustainability challenges and answers, there remains a lack of overarching models that integrate these diverse perspectives into a single, cohesive framework.

2.1.4. Findings

2.1.4.1. From Sustainability Definition to the United Nation Agenda

The theme of sustainability in corporate performance has started to gain unprecedented attention and urgency following the introduction, by political organizations and unions, of international agreements and regulatory frameworks aimed at addressing global environmental challenges. It is thanks to these initiatives, in fact, that a pivotal shift can nowadays been recognized in how industries prioritize and implement sustainable practices [59, 100].

The concept of sustainable development was firstly introduced in 1987 with the publication of the Brundtland Report, formally known as “Our Common Future”, by the World Commission on Environment and Development. Providing the most widely recognized definition of sustainability as *the ability of meeting the needs of the present without compromising the ability of future generations to meet their own needs* [105], the document played a foundational role in shaping the modern understanding and strategic implementation of sustainable development. The report’s primary goal was to highlight the interconnectedness of economic growth, environmental protection, and social inclusion, and the need for international cooperation and collective action

to properly address the transboundary and complex issues of a rapidly changing society. This concept has since become a guiding principle for international policy and academic circles [100], fostering a deeper acceptance of the urgent need to prioritize sustainability in business practices and paving the way for a new current of studies aimed at exploring the feasibility, implementation, and impact of sustainable actions across different sectors. Only three years after its publication, in occasion of the Earth Summit of 1992, the Brundtland Report inspired more than 178 countries to adopt the so-called Agenda 21 [106], which defined a comprehensive plan of action for the creation of a global partnership to sustainable development, improvement of human lives, and environment protection. In the following years, all Member States continued to meet to work together toward the achievement of results, defining goals and missions that could be reached only leveraging on multilateral partnerships and continuous cooperations. On the same course of action, 1998 saw the introduction of the “Triple Bottom Line” approach, which clearly expressed the need for a three-dimensional perspective to measure development, inclusive of focus on people, planet, and profit [100]. A measurement of earnings was no more sufficient to assess sustainable development because, within the TBL approach, organizations became also social and environmental entities in addition to their economic characteristics.

With its clear definition of a framework for sustainable development, the Brundtland Report remained a critical reference point for evaluating current sustainability efforts and challenges, inspiring in 2015 the adoption of the 2030 Agenda for Sustainable Development, with 17 key objectives at its core. These Sustainable Development Goals (SDGs), defined to address global challenges such as poverty, inequality, climate change, environmental degradation, peace, and justice [106], have since then significantly shaped policies and strategies across nations and industries.



Figure 10: Sustainable Development Goals

A multitude of green initiatives has spurred from the UN's agenda, encouraging both public and private sectors to incorporate sustainability into their operational and strategic frameworks. Among the many, advancements in renewable energy technologies, smart urban planning [22, 45], and integration of circular economy principles [54, 72], all reflecting the agenda's call for a sustainable development that is both inclusive and environmentally sound. In the research landscape too, the advent of SDGs has been responsible for a notable shift, with authors progressively focusing on works that can explore and validate technologies and methodologies that align with the United Nations' objectives.

2.1.4.2. The Origin of sustainability Reporting Standards

Together with the publication of the Brundtland Report, another major event impacted in the same years on environmental awareness and legislation, highlighting the importance of corporate reporting as a tool for communicating stakeholders the effects of an enterprise's activities on the environment. This turning point is represented by the Exxon Valdez oil spill in 1989 [100], which determined the pouring of millions of gallons of crude oil onto the coast of Alaska, causing extensive damage to the marine environment and local ecosystems. The disaster, which is still nowadays one of the most catastrophic of US history, not only sparked public outrage and led to significant legal consequences for Exxon, but also served as a catalyst for changes in

environmental policy and corporate practices, including sustainability reporting [100]. In the same year, in fact, a non-profit organization “The Coalition for Environmentally Responsible Economies” (CERES) was established by a group of environmentalists and investors to point out the need for businesses to reassess their roles and responsibilities as economic, environmental, and social entities. Ten basic principles were published, ranging from waste reduction and disposal to management commitment and audit-reporting, representing the first comprehensive guide in history that aimed to establish ethical environmental behaviours in business activities [100].

In 1990s, many initiatives were undertaken to develop a new reporting methodology for stakeholders based on the principle of sustainable development, and 1997 saw the establishment by CERES of a new project department, the Global Reporting Initiative (GRI), committed to develop an environmental reporting framework together with the United Nations Environment Program (UNEP) support [107]. This latter step is still nowadays considered the cornerstone of sustainability reporting’s institutionalization adventure.

As mentioned in its statement and in line with the recently introduced TBL approach, the GRI’s steering committee aimed at improving the proposed reporting framework to include economic and social impacts in addition to environmental issues, marking the shift from environmental reporting to sustainability reporting [100]. The first version of the GRI guidelines was released in 2000, covering a wide array of sustainability issues ranging from environmental performance, labour practices, human rights, and societal impact. Immediately after that, the GRI was transformed into an independent entity with headquarters moved from Boston (USA) to Amsterdam (Netherlands) [100], and quickly released G2 and G3, updated versions of the first published guideline. In particular, it was the third version, published in 2006, to introduce the concept of materiality, emphasizing the importance of reporting on aspects that are more critical to an organization and its stakeholders. Few years later, in 2010, the United Nations recognized the GRI guidelines as the basis for sustainability reporting, and 2013 marked the publication of G4 [107].

As already mentioned, 2015 represented a pivotal year in the shift toward sustainable responsibility in business practices and, with the definition of the 17 SDGs, emphasis was put on the need for corporate transparency [42, 54]. The following year, GRI launched the first set of Sustainability Reporting Standards, designed to be universally applicable to all organizations, regardless of size, sector, or geographic location. The need for more tailored indications determined then, in 2019, the launch of the Sector Program, which led in 2021 to the publication of the first GRI Sector Standard for Oil and Gas industry, followed then by Coal, Agriculture, and Mining [107].

Nowadays, GRI represents the most widely used scheme for measuring and communicating information related to corporate sustainability, with around two-

thirds of reports analysed worldwide applying its guidelines [108]. However, many other certification initiatives have been developed during the years, reflecting the growing global emphasis on environmental, social, and governance responsibilities. Among them, one of the most acknowledged ones is the Integrated Reporting Framework (IR), developed in December 2013 by the International Reporting Council and merged in 2021 with the Sustainability Accounting Standards Board (SASB) to form the Value Reporting Foundation [94]. Similarly to GRI, the IR aims to improve the way organizations think about, and report on, their overall strategy, governance, performance, and prospects in the context of external environment, but with a major focus on the creation of value for stakeholders over time. Being more strategic in nature and not necessarily on annual basis, the IR is designed to be embedded within the existing corporate reporting process to link financial and non-financial aspects [109]. Fundamentally, while both frameworks share the common goal of promoting transparency and sustainability in corporate reporting, they address the issue from different perspectives, leaving freedom to companies to draft one or both types of documents.

The EU has played a significant role in advancing sustainability reporting among organizations, both within its member states and globally. The first major step took place in 2014, with the publication of the Non-Financial Reporting Directive (NFRD) that required all large companies and groups with more than 500 employees to disclose information about their environmental stewardship, social responsibility, treatment of employees, and anti-corruption efforts [104]. Aimed at increasing comparability in the way organizations presented non-financial data, the achievement of this purpose was unfortunately impeded by variable implementation and enforcement within the member states, determining confusion and heterogeneity among results. Consequently, in 2022, a new version of the NFRD was published under the name of Corporate Sustainability Reporting Directive (CSRD), with the goal of expanding the obligation for sustainability reporting compliance to all companies listed on regulated markets, with the only exception for micro-enterprises. Besides implementing a mandatory report audit to enhance the reliability and credibility of sustainability reports, the new directive also introduced more detailed reporting requirements, currently managed by the European Financial Reporting Advisory Group (EFRAG) [103]. Finally, as a last step of this path, the Corporate Sustainability Due Diligence Directive (CSDD) was published in July 2024 on the Official Journal of the European Union. The directive establishes comprehensive due diligence obligations for large companies to identify, prevent, and mitigate adverse impacts on human rights and the environment throughout their value chains, including not only direct operations but also those of upstream and downstream nodes. Applied to large companies that either were founded in the EU or have significant operations within its borders, the CSDD enforces to develop a plan for ensuring the compatibility of business strategy with the Paris Agreement goal of limiting global warming to 1.5°C

and charges directors to set up and oversee the implementation of due diligence processes in corporate strategy. From 2014 onwards, all these documents were drafted with the goal of encouraging companies to disclose information according to the double materiality principle, which considers both the impact of organizations over the environment and the influence that sustainability and climate change have on companies' financial performance and operations.

2.1.4.3. Sustainability in Business Practices

With the theme of sustainability gaining so much attention in the political landscape, and with the first obligations and regulations released, companies worldwide started in the second half of the last decade to committedly interest to the issue. Sustainable development not only became a mean for higher eco-efficiency, lower negative impacts on health and environment, and economic success [59], but also a necessary tool for gaining attractiveness in the eyes of potential investors and stakeholders [19]. Probably due to the high rate of environmental catastrophes of previous years, companies slowly recognized the fundamental role of sustainability as an instrument for brand image improvement, as reputation suffered a massive discount when ESG was poorly managed [101]. The definition of corporate responsibility soon extended beyond the mere economic perspective, and environmental and social commitment became tools for prosperity [23, 24, 31, 37], higher competitiveness, and risk reduction [30, 35, 53, 54, 55]. The latter, in fact, revealed to be closely intertwined with sustainability, as organizations recognized the impact of ESG factors on financial stability, and proactive engagement with investors on related matters resulted to be a tool for enhancing access to capital, reducing associated costs, and strengthening the market position [60].

With population growing and climate change becoming always more pressing, the focus shifted from short term performance to long term resilience and efficiency [24, 48], and incremental attention has been given to food waste, GHG emissions, and chemical pollution [27, 89]. Because of the high power as social players, large companies became the fulcrum of change, leading to 80% of the 250 most influential multinational enterprises publishing corporate sustainability reports by 2020 [108].

The COVID-19 pandemic gave a significant impetus to corporate sustainability, as the crisis highlighted the interconnectedness of environmental, social, and economic challenges [18, 43]. Many businesses recognized the importance of resilience and adaptability in their operations, consequently deciding to shift toward more localized and sustainable supply networks, and the social dimension ceased to be overlooked. Indeed, firms started to invest in their communities and to support employee well-being by improving labour practices through digitalization of processes and better working conditions [34, 49, 50, 59, 60, 94]. Thanks also to the momentum coming from the amalgamation of digital technology and traditional sectors [53], a significant

increase in sustainable investments took place, with companies trying to integrate resilience into their business strategies and cities and governments working together toward a low-carbon and resource-efficient society [40].

With the concepts of circular economy and bioeconomy strategy moving forward, the need for collaboration between public and private sectors and across the value chain has become always more important [49], and the need for cooperation between cross-departmental teams has turned into a pivotal element of business architecture [59]. Moving away from the simple idea of wise resource usage, sustainability has become synonym of competitive advantage, accountability, and legitimacy [22], as well as an instrument for investment attraction, improved corporate image, and informed decision making [58]. In this regard, employee engagement has started to appear as a crucial factor in embedding sustainability into the core of corporate operations [94], as it fosters a sense of purpose, commitment, and responsibility among staff [60]. Indeed, involvement through training and awareness programs, formation of green teams, and integration of sustainability goals into job roles and evaluations, makes employees' personal values aligned with corporate mission and pushes them to actively contribute to sustainability efforts [60].

However, despite the growing importance of sustainability, and the undeniable recognition of its significance, companies have long struggled to properly measure their efforts and often lack appropriate, actionable strategies to implement it into their businesses. During the first years after the implementation of the NFRD, it was common to see organizations referencing only what was easy to measure instead of what truly relevant for the company's operations [59], and business culture was still focusing predominantly on short-term financial performance [28]. The lack of a compulsory set of sustainability reporting rules and standards, combined with the fear that sustainable practices may be unprofitable [38], led very few companies to implement responsible strategies and determined great hesitation in adopting GRI framework [57]. Moreover, even if recognized that economic success cannot discern from environmental and societal effort, there was still a recurrent disconnection between these dimensions and the financial one [49].

With years passing, and with academic research on the topic slowly intensifying [54, 97, 99], larger companies have progressively started to embrace sustainability into their businesses, but always in an approximate way and with little coherence. While it still results difficult to properly measure and report impacts in term of social dimension, the environmental one has started to be slowly taken into account [30], with energy and waste management as primary focus [53, 70]. Unfortunately, however, the lack of an appropriate and standardized framework makes everything more challenging, and companies often tend to prioritize the adoption of own methods instead of more homogenous and universal ones [30, 60]. This, with the rapid pace of regulatory changes, means that no sooner do companies become compliant with one framework than another is issued, continually disrupting compliance efforts [60].

Sadly, there are still clear gaps in the projected linear trajectory proposed by Europe target 2030 [40], and the difference between SDGs, which focus on universal metrics such as poverty, health, and education, and companies' perspective, which focuses on community and context-specific metrics [50], certainly doesn't help.

2.1.4.4. KPIs for Sustainability

As already mentioned, companies can leverage on a broad selection of frameworks when it comes to sustainability assessment, with academic literature and practitioner field identifying around 100 sustainability and impact management and measurement models around the world. However, the expressed recommendations are still on voluntary basis, and companies can decide what to disclose and to what extent [37], often leading to a specific focus on only one of the three sustainability perspectives proposed by the TBL [53]. Moreover, additional confusion and heterogeneity are provided by the absence of a single and official document that companies have to draft in relation to sustainability, with the result that many possible layouts exist to make reading complex and articulated [30, 54, 95].

Providing an extensive collection of KPIs and indicators from which to choose [57], GRI leaves companies the possibility to create their own dashboards and focus on concerns that are specific to the industry [49], which is a strength from a certain point of view but a significant drawback from the other. It is not rare, in fact, to notice inconsistencies in the data presented, making it challenging for investors and other stakeholders to conduct direct comparisons even within the same sector [40, 56, 59]. Companies are somewhat allowed to select only those indicators associated with good sustainability performance, while omitting areas where results are weak and necessitate further improvement. Moreover, especially for smaller companies, the vast array of KPIs from which to choose can be often overwhelming and resource-intensive, leading to difficulties in effectively measuring and reporting without experts' help [90].

Prior to 2016, very few companies were attempting to sustainability, but not necessarily in a very strategic way [60]. The main obstacle was a lack of technical support, as companies were doing everything in Excel [45], encountering enormous complications, and there were no tools for getting information about environmental impact. The few developed indicators were not sufficient to cover all needs, and non-financial disclosures often ended with being in a story-telling format [19, 50], as data only could not provide everything useful [60].

After the release of the first obligation for non-financial reporting, companies started looking for digital solutions that could fit with their business, but a major challenge was represented by the absence of any specification on what non-financial information to disclose [60]. Initially, most companies went to the ESG framework Nasdaq [60],

which was likely a fine start, but after only a couple of years it became evident that managers needed something more tailored to their operations. Some organizations attempted to program their own IT solutions and access data from data sources no partner had access to, but this was challenging and provided threats, as in the current sustainability environment companies must be certified for what they do and how they do it [30], and this is not always possible when making own solutions from scratch [60].

Another big challenge came when companies were asked to look at their extended value chain when thinking strategically about their sustainability impact, as data had now to be gathered not only within the organization's boundaries but considering all the suppliers and partners as well [41, 42, 55]. EU Taxonomy and all the other regulations demand data that companies often lack and which available IT systems cannot manage, at least in a precise way. Additionally, the continuous release of updated requirements and obligations contributes to make the sustainability reporting ecosystem even more confusing, as managers often fail to understand what current and forthcoming requirements mean in terms of sustainability disclosure [60].

From an academic point of view, the theme of sustainability assessment has gained particular attention since the second half of the last decade, when the new obligation for large companies to disclose sustainability-related information made it necessary to finally look at the issue from a quantitative perspective. However, if we consider the scope of the phenomenon, it is not addressed as it should be, and there is a shortage of valuable scientific studies developing techniques for quantifying extra-financial dimensions and evaluating the dynamic of KPIs [20, 32].

The idea of indicators' purposefulness [59], which first arose in the 1990s with the development of the Balanced Scorecard by Robert Kaplan and David Norton [94], gained great attention during the years of sustainability regulations release, as companies understood the need to focus only on those dimensions that were relevant for their business. In front of the vast proposal by GRI [57], organizations are asked to choose KPIs according to their specific industry requirements and taking into account the interests of their own stakeholders, whose satisfaction is always a prerequisite for success [51, 59, 90]. Not only, their engagement indeed helps identify emerging sustainability issues, respond to changing expectations, co-create solutions considering broader interests, enhance corporate reputation, risk mitigation, and social license to operate [31, 50, 57, 60]. At the same time, indicators should be smart, clear, and achievable to fulfil the purposes of improvement, and limited in number to ensure better measurability and traceability of performance [50, 51, 55].

Many initiatives have begun with the aim to draft comprehensive and adequate indicators, but no convergence in the definition and deployment of application methodologies has ever been reached [48], with the result that organizations still nowadays struggle to select and apply the appropriate ones. While companies should

use both quantitative and qualitative measures to assess their performance, a narrative style or prose text must be avoided [101], and results should be communicated in the most comprehensible and comparable way.

The meaning of indicators has always been to ensure objective quantification of outcomes, comparability within years, and rapid detection of problematic situations that need to be addressed and improved. By now, however, besides not being correctly and universally defined, indicators are usually computed through rigid spreadsheets that revolve around average and approximate values, making their evolution and customization tedious and error prone [45]. Moreover, existing literature is largely based on qualitative measurement systems and binary-based surveys [19], which often fail to capture the nuanced realities of business environments and the complexity of various organizational processes. To address these challenges, and to ensure more reliable internal and external benchmarking, there is a growing emphasis on developing dynamic, data-driven KPI systems that leverage advanced analytics, machine learning, and real time data processing. These technologies, in fact, have the potential to enable a more accurate, comprehensive, and flexible approach to performance measurement, allowing organizations to adapt more swiftly to changing conditions and to optimize their strategies more effectively [32, 90, 94].

Environmental

Among the three pillars of sustainability, environmental perspective is certainly the most addressed one. Following the many environmental disasters that characterized the end of 20th century, such as the already mentioned Exxon Valdez oil spill of 1989 and the Bhopal gas catastrophe of 1984 [100], countries begun to understand the importance of preserving biodiversity and catalysing the green movement. Starting from 1970, with the institution of the Environmental Protection Agency (EPA), many regulatory actions were issued to help the fight against climate change, leading to a deep focus on this dimension long before social sustainability. The Paris Agreement itself represented a landmark in the multilateral climate change process, setting a challenging target for emissions reduction that can be achieved only through the collaboration and reciprocal support of all nations together [52, 60].

Being easy to quantify and directly measurable, and also characterized by global repercussions, environmental sustainability appeared as the most impellent issue to solve, calling companies worldwide to contribute to change. International bodies soon started to work together for the development of standardized KPIs that could be applied across border to facilitate coordinated action, and recent technological advancements have made it easier to monitor and report necessary data.

Nowadays, an always increasing number of companies include environmental assessment in their annual reports [27], and the most addressed aspects to be measured are carbon footprint, energy consumption, water usage, waste management, and

biodiversity impact. Unfortunately, a standardized and homogeneous set of KPIs does not yet exist, and organizations often face the challenge to select the most appropriate ones and modify to their necessities. Moreover, despite the urge of digitalization in most recent years, companies often struggle with accurate data collection, having difficulties to obtain the necessary information for KPIs calculation and often ending with using approximate estimates that falsify the results [41, 60].

Social

Together with environmental concerns, the concept of corporate social responsibility began to take shape in the 1950s and 1960s, but only in terms of philanthropy and ethical practices. It wasn't until the 1990s that focus started to move on more diversified issues, such as global labour practices, human rights, and social impacts of globalization [49, 59], and it was only with the GRI publication that general guidelines were defined for providing a structured way of reporting. Many years had to pass until the EU Non-Financial Reporting Directive (NFRD) officially required companies to disclose information about social and employee-related aspects, such as respect for human rights, anti-corruption and bribery issues, and diversity on company boards [53]. Only at this point companies really started to integrate the social perspective into their non-financial reports, which were until this moment filled with only environment related information, mainly because of the fear of fines and legal penalties.

Probably due to this later definition, but also to the harder measurement, companies tend to reserve littler importance to social performance in respect to environmental and economic ones [31, 52, 55], often failing to disclose all the relevant information that should be communicated to stakeholders. Most utilized indicators include employee turnover rates, gender pay equity, training opportunities, and community development contributions, but broader societal impacts are often overlooked. Moreover, if it is true that lack of homogenization is recognized in the use of environmental KPIs, the issue becomes even more relevant when looking at the social dimension, where most of metrics are qualitative and subjective, hard to measure and difficultly benchmarkable [33, 57].

Governance

Governance, which entails the practices and policies that a company adopts to govern itself, make effective decisions, comply with the law, and meet the need of external stakeholders, began to gain prominence as an important issue among companies in the late 20th century, following the concretization of some major events and trends [100]. The introduction of the Foreign Corrupt Practices Act of 1977 represented the first attempt to prevent bribery of officials and marked an early step towards more comprehensive regulations, which majorly intensified in the late 1990s and early 2000s.

During these years, in fact, a series of high-profile corporate scandals, such as the ones of Enron in 2001 and WorldCom in 2002, led to a loss of investor trust and highlighted the need for stricter governance regulations that could protect from fraudulent accounting activities by corporations. The importance of strategic risk management and transparency in operations was then further stressed with the Global Financial Crisis of 2008 [30], which renewed the focus on ensuring cohesion and clearness in business conduction. In more recent years, and specifically after the introduction of the Corporate Social Responsibility concept, governance practices have begun to encompass broader issues such as environmental stewardship, social impact, and ethical management [36], putting emphasis on inclusion and diversity, wages and work conditions, data management and cybersecurity [55]. In this regard, 2018 saw the enforcement by EU of the General Data Protection Regulation (GDPR), which has been built to enhance the rights of citizens concerning several core data protection principles, such as lawfulness, fairness, transparency, integrity, and confidentiality [110].

Unfortunately, despite its critical role in ensuring long-term sustainability, governance is often the least highlighted among the three pillars of sustainability, probably overlooked because of the internal nature of its impact. Indeed, among the analysed papers, it has been not rare to find articles that completely disregarded the governance dimension or to recognize the subsumption of related KPIs under the social or economic categories, which are typically more emphasized because of the direct impact on communities and stakeholders. Many authors talked about the importance of ensuring transparency of operations and good communication [30, 37, 56], but only few recognized the existence of specific metrics that could be used to monitor and demonstrate the commitment to sustainability from an organizational and managerial point of view [88]. Typical indicators concern board composition and structure, ethics and compliance, traceability and transparency, and are all devolved at embedding sustainability within corporate strategy, engaging stakeholders in decision-making, and enhancing trust while demonstrating commitment to environmental and social issues.

2.1.4.5. Digitalization and Sustainability

Digitalization refers to the process of converting information into a digital format, enabling data to be easily stored, processed, and transmitted by electronic devices. It relies on the use of computers, mobile devices, the internet, and other technologies to manage and transmit information, giving the opportunity, together with other technologies such as big data analytics and artificial intelligence, to analyse large datasets quickly and with greater precision. In business context, it determines the possibility to automatize existing processes and to create new ones that can better meet market requirements and support decision making.

This revolutionary process started to gain importance significantly in the latter years of the 20th century, and reached its maximum pervasiveness in the early 2000s, when the use of Internet spread over and broadband connectivity made its first appearance. Since then, businesses, governments, customers, and researchers increasingly recognized the efficiency and opportunities presented by digital technologies, and various aspects of daily life, business operations, and governmental functions started to be transformed. The introduction and adoption of smartphones and cloud computing marked then another crucial phase, with people being finally able to access digital services and information from everywhere and companies leveraging virtual platforms for storing and processing data. From 2010 onwards, with the rise of artificial intelligence and big data analytics, digitalization of processes gave the possibility to businesses to personalize services, predict outcomes, and automatize operations, paving the way for a completely new method of conducting daily practices.

In the contest of our literature review, the growing importance of digitalization is evident by the focus on the linkage between the above-mentioned process and sustainability performance, with more than a half of selected papers addressing the theme and most of them published in the last four years, starting from COVID-19. The majority of studies focus on understanding how digital technologies can impact sustainability performance, including both opportunities and challenges, and how it can support the achievement of sustainable development goals (SDGs). Many authors questioned whether digitalization is actually convenient, given its expansive reach and profound impact on economic, social, and environmental spheres [84]. Indeed, while it undeniably accelerates efficiency and broadens accessibility, it also introduces complex challenges such as data security concerns, privacy issues, and significant digital divides that could potentially exacerbate existing inequalities.

Starting from the late half of 2010s, companies have begun to recognize the usefulness of digital and information technology for gathering and analysing data [37], and the phenomena has become even more evident with the first appearance of artificial intelligence and machine learning [63, 73, 81]. As the landscape becomes increasingly competitive, the shift toward digitalization is embraced as an inevitable, pivotal resource for achieving strategic objectives across sectors. The “digital imperative” leads companies to harness and expedite the digital transformation process [99], and is nowadays a priority on the agendas of many governments worldwide, which may be accused to have focused more on economic growth than preserving the foundations of that growth [75]. At the same time, however, the urge of climate issues and the new adopted regulations highlighted the necessity for companies to progress toward a more responsible corporate behaviour, making sustainability the core of their strategy and engaging stakeholders for the achievement of better results. It is at this point, then, that these two terms, sustainability and digitalization, which long appeared as disparate ones, started to stand as the most important megatrends shaping our

economy and society [70, 99], game changers and strategic imperatives able to trigger major transformations.

Leading organizations are progressively adopting digital solutions to reconfigure their business models to address societal challenges more effectively, and it is undeniable their potential to propel economic growth while alleviating environmental pressure [53]. However, the application of digital technologies in sustainability still remains partly unexplored and a lack of concrete evidence avoids getting rid of the scepticism about digitalization's positive effects [99]. In particular, while it is clear that digitalized processes reduce operating times and necessary resources, their intensive energy consumption still make managers wonder if it is necessary for improving sustainability performance or not [71, 75, 79, 84, 86, 93]. In particular, even if providing advancements and improvements in the medium and long term, the initial adoption of digital technologies may lead to increased energy consumption and emissions, especially in some specific context as for example transportation [52]. Moreover, the convenience of digitalization depends on the complexity of the procedure to be transformed, as it should not be taken for granted that human and manual processes always consume more than automatic ones [52, 84]. In the last years, in fact, many companies have undertaken a transition toward digitalization mainly because of the accepted truth that it makes organizations smarter, but negative impacts can be higher than positive ones if pros and cons are not correctly evaluated and if a quantitative analysis is not carried out before implementation [52]. Indeed, the transition is often unsuccessful when companies decide to purchase off-the-shelf digital solutions, as they hardly align with the specific business needs and then force substantial investments into customization [60].

From an environmental point of view, data centres are significant energy consumers and contribute to higher carbon emissions if not managed sustainably and if powered by fossil fuels instead of renewable resources, as it often happens. It is indeed not surprising that by 2040 the environmental impact of ICT is expected to represent 14% of the total global footprint at the 2016 level, surpassing almost half of the current total footprint of the industrial sector in the United States [111]. Moreover, the rapid obsolescence of digital devices can lead to significant amount of electronic waste, posing challenges for waste management and recycling systems and negatively impacting on the achievement of SDG 11 [73, 75, 89]. Privacy too becomes an issue when dealing with digitalization, and the potential for security breaches poses significant risks that need to be managed carefully if organizations want to avoid the possibility of losing control of their data [60, 89, 96, 98].

Finally, from a social point of view, the spread of digitalization threatens to exacerbate social inequalities if access to technological tools and internet is not equitable, leading to hindered ability for disadvantaged groups to benefit from digital advancements in education, healthcare, and economic opportunities [89, 96, 98]. Companies as well can undergo a similar process, with the gap between well-resourced firms and smaller

enterprises aggravated by the impossibility of the latter to collect the capital required for investing in the earlier phase of operations digitalization [60].

Despite all these potential drawbacks, however, digital tools have consistently demonstrated their power to enhance efficiency, enable smarter resource management, and foster inclusive growth, which are all essential for achieving the SDGs [53, 79, 86]. Smart grids, smart meters, and intelligent systems can provide real-time energy monitoring and management [39], reducing unnecessary consumption and supporting the shift towards renewable resources usage. It has been demonstrated, for example, that using digital tools for optimizing logistics can minimize travel distances and times, thus reducing fuel consumption and greenhouse gas emissions.

Technologies like IoT sensors and artificial intelligence, combined with data analytics, can predict maintenance needs and optimize routes and inventory, reducing waste in both resources and time and improving the overall efficiency of production and distribution processes [44, 47, 68, 88]. Blockchain, on the other side, can provide transparent tracking of products assembled through different sources, ensuring compliance with environmental standards and preventing practices like illegal fishing [42, 47, 55, 83]. At the same time, features such as interconnection and sharing of digital technologies complete organizational disintermediation, which aids in enhancing ineffective processes within the enterprise and leads to an upgrade of the organizational structure to a more agile and highly resilient model [53, 73].

Moreover, from a social perspective, the introduction of digital technologies has revolutionized healthcare by improving access and quality of services in both developed and underserved regions [33], directly contributing to the third sustainable goal related to good health and well-being. In the context of corporate sustainability, it has the power to alleviate drawbacks such as barriers to knowledge flow, industry monopoly, outflow of skilled personnel, female board disadvantage, and the aging board problem [53]. Most of all, however, digital tools play a pivotal role in enhancing transparency in business operations and supply chains, allowing stakeholders to be better engaged in decision making and more inclined toward promoting environmental, social, and governance practices [37, 42, 53, 70]. Diminishing information asymmetry, digitalization elevates optimistic market outlooks, enhances business performance, effectively improves stock liquidity levels, and facilitates the identification of potential business opportunities and environmental threats from a multidimensional perspective [50, 53, 73]. Fundamentally, digital transformation can be seen as one of the most important ways in which companies can achieve sustainable growth while adapting to the rapidly changing market environment and technological advances.

As papers highlight, the concept of digital sustainability has gained impressive relevance in the last few years, and is certainly going to acquire more. Considering the

strong government support for industry digitization and digital industrialization [53, 72, 80, 84], information technologies hold significant promise for advancing sustainability across multiple sectors, but inclusive policies and a balanced approach are needed to maximize benefits and minimize risks. By now, many academics have investigated the impact of digital transformation in enterprises [75], but the majority of literature has concentrated on economic implications only, emphasizing the enhancement of internal efficiency and the external environmental perceptions of micro-firms [65, 44]. Articles studying the consequences of digital tools on environment and society do not miss, but their number is certainly limited if we consider the vast scope and rapid pace of technological advancements and sustainability requirements [60, 96]. Despite growing interest in this area, in fact, research mainly focus on economic benefits, which are certainly easier and more quantifiable to measure, overlooking the critical importance of digitalization as a tool for enhance also environmental and social performance. This, combined with the fact that technology constantly evolves, making it challenging to conduct evaluations in the long term, highlights the need for more comprehensive and ongoing studies that keep pace with the dynamic nature of digitalization and account for all possible repercussions [60].

2.1.4.6. Summary of Findings

The exploration and analysis of the selected 83 articles, complemented with the reading of a few major extra-academic papers, contributed to set the stage for future research and helped gaining a comprehensive understanding of the study context.

In terms of sustainability assessment and digitalization integration, corporate practices have been long and significantly influenced by historical developments, international policies, and technological advancements. Starting from 1987, with the publication of the Brundtland report, the business world has progressively shifted toward a more responsible way of conducting daily operations [100], and organizations have been called to demonstrate their effort in changing behaviour and fighting against climate change. Only few years later, the introduction of the Triple Bottom Line concept strengthened the standards and expanded the scope of interest from purely environmental reporting to include social and economic dimensions, making it imperative for companies to adopt a more holistic view of their impact [23, 58]. With the beginning of the new millennium, the release of the first version of GRI guidelines marked a renovated commitment toward sustainability, and the following publication of regulations and statements by international corps enforced this promise even more.

Contextually to the spread of sustainability, companies started to embrace the digital transition and to modify the way of doing business and keep trace of results. The advent of big data analytics, artificial intelligence, and IoT soon demonstrated the possibility to improve quality and efficiency while reducing costs and facilitate

teamwork, encouraging organizations worldwide to implement them within their business processes [69]. The possibility to gather and analyse data in real time represents a great advantage in the field of sustainability assessment, but despite companies recognizing the need for clever and updated reporting methodologies, a concrete implementation of these technologies is often hindered by several challenges and not at point [60]. As a result, while the theoretical benefits are widely acknowledged by business world and academic researchers, the practical application within the realm of sustainability assessment remains patchy and inconsistent.

By now, companies still struggle to effectively disclose non-financial information related to their sustainable performance, and the lack of standardized and harmonized templates can be recognized as one of the major causes [56]. The existence of a vast proposal of possible KPIs from which to choose, combined with the unclear definition of each of them, determines confusion in sustainability assessment, with organizations ending following their own methodologies instead of universal guidelines. Moreover, the previously mentioned incapability to properly leverage ICT potentialities leads companies to compute KPIs through rigid spreadsheets that not only require human intervention, and therefore determine waste of time, but also facilitate errors and miscalculations [45]. While the implementation of digital tools could easily provide real-time data gathering, indicators are usually calculated through approximate and average values that do not reflect the actual performance, leaving the overall view always inaccurate.

Research on the topic has certainly intensified during the last years, but the number of available studies is still insufficient taking conscience of the issue's significance in business practices and daily life [32, 99]. While articles tend to focus on specific sectors and industries to carry on their evaluations, the world needs a more generalized and comprehensive analysis that clearly suggests what companies should measure and how they should do it. The 2030 deadline is not so far anymore, and despite considerable progress has been made in the development of sustainability practices and reporting standards, significant challenges remain and need to be addressed [40, 89, 96].

The absence of a unified methodology for assessing the impact of sustainability hampers in fact the ability to track progress towards global sustainability objectives, such as those outlined in the United Nations Sustainable Development Goals (SDGs), and also limits the potential for sharing best practices and learning from successful initiatives [60]. Moreover, the issue is further exacerbated by the ever-evolving regulatory landscape, which can render newly implemented technologies obsolete or inadequate for new regulatory demands, thus risking the investments made into these technologies.

In response to these challenges, the call for a common global methodology and information disclosure platform is strong, aiming to standardize impact assessment

and enhance transparency and stakeholder engagement towards a low-carbon, equitable society. Yet, establishing this tool requires collaborative efforts among governments, NGOs, the private sector, and international organizations to develop and adopt universal standards and reporting guidelines that reflect the complexities of sustainability while being practical and accessible for diverse users [24, 41, 48, 72]. The primary concern lies in selecting and implementing digital technologies that precisely match an organization's specific sustainability objectives, operational requirements, and strategic outlook. Once done with that, allocating adequate resources to bridge the technological and knowledge gaps between software solutions and sustainability reporting requirements is vital for effective implementation [60].

2.1.5. Limitations

The literature review has been conducted with the goal to critically examine the intersection of sustainability and digitalization within corporate practices, with a specific focus on the challenges of non-financial reporting and the influence of digital technologies in both monitoring and enhancing performances. Through a detailed exploration of current frameworks and recent trends, the review has highlighted the usefulness of digital tools as both resources savers and performance trackers, underscoring their potential to streamline and improve reporting practices.

However, despite the comprehensive nature of this review, which took into account more than 80 articles and some non-academic documents, there are few limitations that must be acknowledged and potentially overcome in future research.

Papers were mainly selected from peer-reviewed journals indexed in the Scopus database, determining the possibility that other relevant studies, published in other outlets but equally insightful, may have been excluded. At the same time, the decision to focus on articles only entailed the neglect of material published in other formats, such as books or conference papers, that may have been helpful for gaining an alternative perspective or collecting additional insights.

Some papers were automatically excluded from the analysis because unavailable in English or inaccessible due to subscription barriers, potentially restricting the diversity of perspectives and methodologies considered. Similarly, the concentration of articles in the European country could be symptom of an intrinsic geographical bias associable to the nature of the source database.

Finally, it must be considered that some of the findings previously exposed are contingent on the accuracy and comprehensiveness of the original researchers' work, meaning that eventual misinterpretations or methodological flaws in primary studies could have been incorporated into the review itself. Especially in the case of experimental research and comparative studies, in fact, the robustness of results is

directly relatable to the reliability of the developed analytical models and background assumptions.

The acknowledgment of these limitations not only helps contextualizing the exposed findings but should also encourage future research to embrace a more inclusive and diversified approach that could keep pace with the dynamism of sustainability reporting and the role of digitalization in this domain.

2.2. Existing Methodologies

2.2.1. Introduction

While the previous section offered a comprehensive overview of the current academic landscape on sustainability and digitalization, highlighting trends, frameworks, and key performance indicators, this new part aims to shift the focus from *what* is being measured to *how* the underlying dynamics are conceptualized and analysed. In other words, rather than exploring definitions, reporting standards, or isolated variables, this section investigates the existing methodologies used to model relationships among variables and between those variables and a defined sustainability outcome.

This distinction is both necessary and deliberate because, as organizations increasingly commit to sustainability goals and explore digital tools to support them, there remains a significant gap in the understanding of how different factors interact, how change mechanisms unfold, and how intended outcomes can be attributed to specific interventions. In particular, despite the growing body of literature identifying sustainability KPIs, there remains limited clarity on the structural connections between controllable inputs, intermediate levers, and resulting impacts, especially within complex socio-technical systems such as sustainability or digital transformation projects. The understanding of these relationships is essential for building effective monitoring systems, for designing coherent strategies, and for anticipating indirect effects and trade-offs.

For this reason, this section stands as a complementary and specular counterpart to the previous one as, while Chapter 1.1 established the content and structure of sustainability assessments, it explores the structure of reasoning and modelling that allows researchers and practitioners to capture causal relationships, represent complexity, and derive meaningful conclusions.

2.2.2. Methods Selection

In line with the objective of this chapter to understand how different variables interact and contribute to sustainability outcomes, sources collection centred on modelling

approaches specifically designed to represent relational structures within complex systems. The methods considered were not selected for their descriptive or diagnostic qualities alone, but for their capacity to provide a structured and interpretable logic that links input factors, contextual levers, and observed or expected outcomes.

Given the vast landscape of available methodologies, and considering the ultimate goal of assessing how and to what extent digitalization influences sustainability, a preliminary framing was necessary before conducting the literature search. Focus had to be reserved on approaches able to ensure a transparent and systematic representation of causality, interdependence, and change dynamics, particularly within socio-technical systems. These include visual frameworks, system dynamics tools, simulation models, and structured decision-support methods, many of which already applied in domains ranging from public health and education to infrastructure planning and ESG evaluation.

The final set of models was not chosen based on disciplinary tradition or popularity alone, but rather on the basis of their ability to meet the analytical needs of this thesis and its highlighted objectives. In particular, each model was ultimately selected based on its distinct way of addressing key challenges such as:

- mapping the relationships between inputs, intermediate variables, and final outcomes
- accounting for feedback, uncertainty, or contextual factors
- enabling prioritization, weighting, or comparison across sustainability dimensions

As a result, the review was structured around four broad methodological families, selected to ensure consistency with the modelling capabilities defined earlier while also providing a conceptually coherent and academically grounded basis for comparison. In this way, each group reflects a distinct modelling logic but complements the others in addressing the complexity of sustainability-oriented interventions in digitally enabled contexts. Specifically:

- **Theory-Based Models** were selected for their ability to define sequential or conditional pathways of change grounded in explicit assumptions about how interventions lead to intended outcomes [112]. Rooted in program evaluation literature, these models are especially valuable for strategy design, planning, and impact mapping, as they offer a structured yet flexible framework to articulate the “theory” behind an initiative [120].
- **System Dynamics and Participatory Models** were included for their strength in representing non-linear interactions, feedback loops, and time delays, as well as their capacity to incorporate stakeholder perspectives through participatory modelling. This family combines traditional System Dynamics tools with Cognitive and Participatory extensions, reflecting the fact that many modern approaches, such as Group Model Building (GMB) and Fuzzy Cognitive Maps

(FCM), blend simulation logic with collaborative processes [115]. Indeed, while structurally distinct, these methods are grouped together because they share the goal of understanding how complex system behaviours emerge from interdependent variables and dynamic feedback. The analytical foundation for this family is rooted in Sterman's (2000) systems thinking paradigm [123], complemented by participatory systems approaches introduced in evaluation and public health literature.

- **Structural and Statistical Causal Models** were selected for their capacity to empirically quantify causal pathways, including both direct and mediated effects, and to test hypotheses about relationships between observed and latent variables [113]. Particularly suited for contexts requiring rigorous validation of complex interdependencies, the key reference for these models' categorization is Pearl [113], who formalized the use of structural causal models in scientific inference and whose framework underpins many applications of Structural Equation Modelling (SEM) and related techniques. Models of this class are coherently expected to display particular emphasis on formal causal structure, hypothesis testing, and fit assessment [141].
- **Evaluation and Prioritization Frameworks** were included for their essential role in supporting structured decision-making in the presence of multiple objectives, stakeholder interests, or trade-offs, which is typical in sustainability-related environments [114]. While differing in purpose and method, models in this family share a common focus on translating complexity into actionable guidance, including both impact evaluation frameworks and multi-criteria decision-making tools [149].

These four families, while distinct in their logic and use cases, are complementary in scope and together provide a robust and multidimensional foundation for exploring how digital technologies interact with sustainability systems.

2.2.3. Collection Method

Following the definition of the modelling criteria and analytical scope, a targeted literature search was conducted to identify relevant academic and institutional sources that apply, develop, or critically assess the modelling approaches aligned with the four methodological families previously introduced. The goal was to collect a robust set of documents capable of informing the understanding of how these models are constructed, used, and adapted, with a special focus on contexts involving sustainability and digital transformation.

In particular, to move from high-level categories to actionable research, it was necessary to identify concrete modelling approaches that exemplify the analytical logic of each family. This step was driven by two main principles:

- The need to include models that are widely recognized and methodologically consolidated, either in academic literature or practitioner domains
- The intention to ensure coverage of complementary modelling capabilities, such as visual structuring, empirical validation, participatory mapping, and decision prioritization

The purpose was not to compile an exhaustive list of all models in existence, but rather to focus on a targeted set of representative tools that reflect the modelling needs defined earlier. These approaches, in fact, form the conceptual core of the methodological literature review and will support the later development of a structured framework for analysing the digital–sustainability nexus.

2.2.3.1. Keywords and Initial Screening

Based on this framing, the search strategy focused on identifying papers explicitly referencing and applying specific models within the four families. Conducted primarily on Scopus and ResearchGate, which were chosen for their multidisciplinary coverage and advanced filtering capabilities, the search was complemented by additional sources drawn from institutional repositories and practitioner toolkits provided by organizations such as the W.K. Kellogg Foundation, the U.S. Department of Education, and international development agencies.

As for the previous section, relevant documents were retrieved through different combinations of keywords and Boolean operators, including “logic model”, “impact evaluation”, “causal pathway”, “system dynamics”, “decision support” and, obviously, “sustainability”.

2.2.3.2. Search period

Since the intention was to include both classic and contemporary frameworks relevant to the construction of causal reasoning structures, no publication date restrictions were applied. Indeed, differently from the previous case, where the goal was to analyse the landscape of sustainability assessment and digitalization under the light of recent developments, this review focuses on methodological foundations, many of which retain their relevance and authority despite having been developed decades ago.

In this context, the credibility and influence of a model is not tied to the recency of its publication, but rather to its conceptual robustness, adoption across fields, and continued use in both academic and applied settings. For example, seminal works such as Kosko’s development of fuzzy cognitive maps [135] and Saaty’s introduction of the Analytic Hierarchy Process [149] remain cornerstones in their respective areas, frequently cited and applied in current research and practice. At the same time, more recent 2023-2024 contributions were also included to reflect emerging adaptations and

methodological refinements, especially in domains such as public health, digital policy, and ESG evaluation.

This inclusive approach allowed the review to capture both foundational models and innovative evolutions, offering a richer and more balanced understanding of the modelling options available for structuring sustainability-oriented reasoning.

2.2.4. Papers Classification

Following the first screening phase, a refined set of 42 documents was retained for detailed analysis, selected based on three main criteria:

- The centrality of the modelling approach within the study’s contribution
- The clarity with which causality or system behaviour was explored or mapped
- The direct applicability of the method to the challenge of understanding digital impact on ESG performance

The final corpus displays a considerable diversity in terms of publication type, geographic origin, temporal coverage, and field of application—reflecting the interdisciplinary and global nature of sustainability-oriented modelling practices.

2.2.4.1. Year of Publication

From a temporal perspective, the reviewed literature spans several decades, combining foundational models with more recent methodological developments.

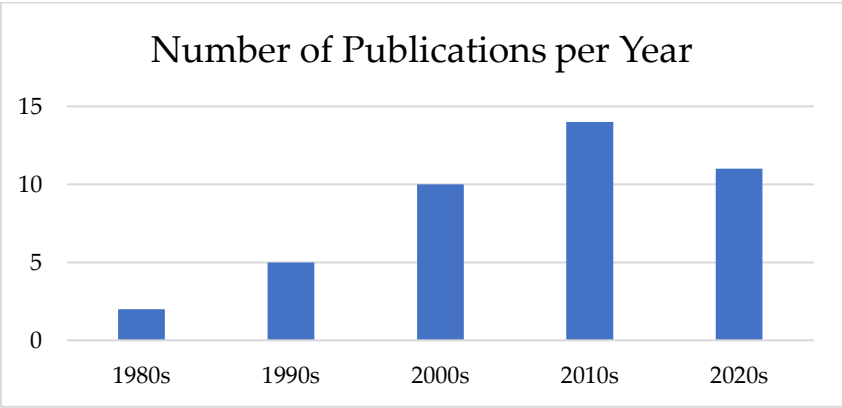


Figure 11: Distribution of Reviewed Papers by Decade of Publication

Classic works from the 1980s and 1990s, often associated with the early conceptualization of evaluation frameworks and decision-support systems, still provide the theoretical backbone for many of today’s tools, but the majority of selected contributions are concentrated in the last two decades, reflecting both a renewed interest in modelling complex systems and the growing urgency of sustainability-related challenges. In particular, the recent surge of publications in the 2010s and 2020s signals a shift towards greater methodological refinement, empirical validation, and

cross-domain applicability, especially in response to emerging needs in public health, ESG reporting, and digital transformation. Interestingly, this distribution also highlights how long-standing models continue to evolve, often through integration with newer data analytics techniques or through adaptation to multi-stakeholder environments.

2.2.4.2. Country

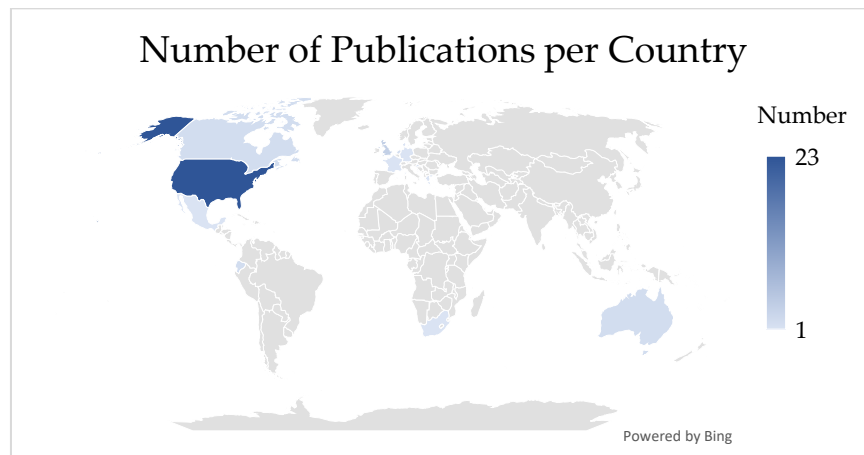


Figure 12: Distribution of Reviewed Papers by Country

The geographical distribution of the reviewed literature reveals a strong concentration of contributions originating from United States, to which it is possible to attribute more than half of total classified documents. This pattern reflects not only the academic leadership and institutional support historically present in the region for evaluation science, systems modelling, and sustainability research, but also the widespread use of formalized modelling approaches within U.S. public policy, philanthropy, and program management. Indeed, many American institutions have played a key role in operationalizing tools such as logic models, theory-based frameworks, and evaluation matrices, driving both the production of methodological guidance and the demand for practical application.

The spatial profile of the remaining papers is notably diverse, with contributions from Latin America, Oceania, and various parts of Europe, each adding valuable variation in methodological approaches and contextual applications. Despite the global relevance of sustainability and digital transformation, however, regions such as Asia and Africa appear underrepresented, pointing to a potential imbalance in the geographical focus of methodological development and application and suggesting an opportunity for future research to expand the modelling discourse.

2.2.4.3. Papers Typology

The classification by resource type helps to illuminate the nature of contributions underpinning the reviewed modelling approaches and the expected use, from abstract theorization to hands-on guidance.

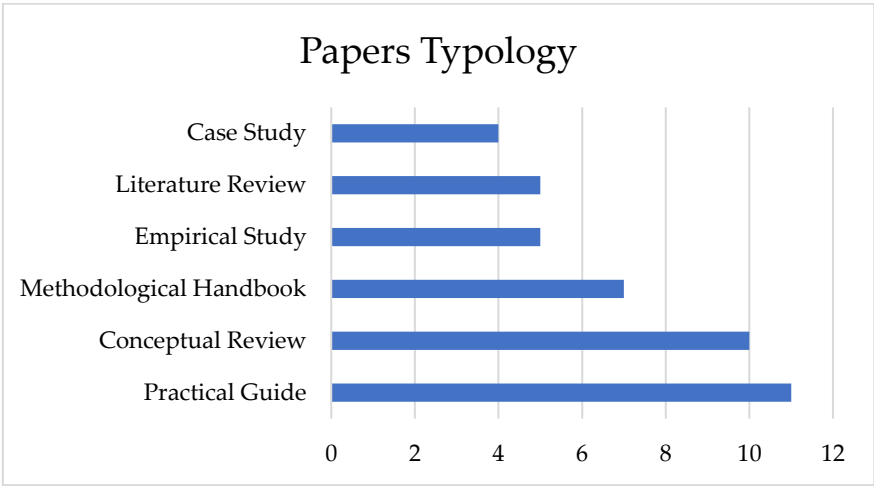


Figure 13: Distribution of Reviewed Papers by Typology

Immediately noticeable is a strong predominance of practice-oriented documents, with step-by-step guides, aimed at supporting users in frameworks’ application, representing the largest share. Their popularity underscores the strong demand for accessible, operational tools in real-world settings, particularly in program evaluation, planning, and sustainability management. Closely following are Conceptual Reviews, which reflect the theoretical core of the field and are essential for proposing, clarifying, or refining modelling constructs without collecting original data. Their presence indicates a sustained academic interest in structuring ideas and building consensus around modelling logic and causal representation, which is especially important in interdisciplinary domains like sustainability and digital transformation.

Methodological Handbooks also occupy a significant portion of the sample. These texts, which are typically more technical in nature and focus on teaching or codifying specific modelling methods, serve as durable references, particularly useful in institutional or academic settings where reproducibility and training are key.

By contrast, empirical contributions are less represented, with Empirical Studies, Literature Reviews, and Case Studies together forming a smaller share of the literature. This relative scarcity of data-driven and evaluative works suggests that, while modelling methodologies are widely discussed and disseminated, their testing, validation, and comparative assessment across contexts is still underdeveloped. Their relevance is however undeniable, as empirical studies typically provide measurable evidence of a model’s effectiveness or accuracy through simulations, field testing, or

algorithmic evaluation, while case studies offer contextual depth and insight into model adaptation or stakeholder response.

2.2.4.4. Field of Application

Categorizing papers relatively to their field of application, it is possible to highlight the interdisciplinary scope of the reviewed literature and the varied domains in which modelling approaches have been developed or applied.

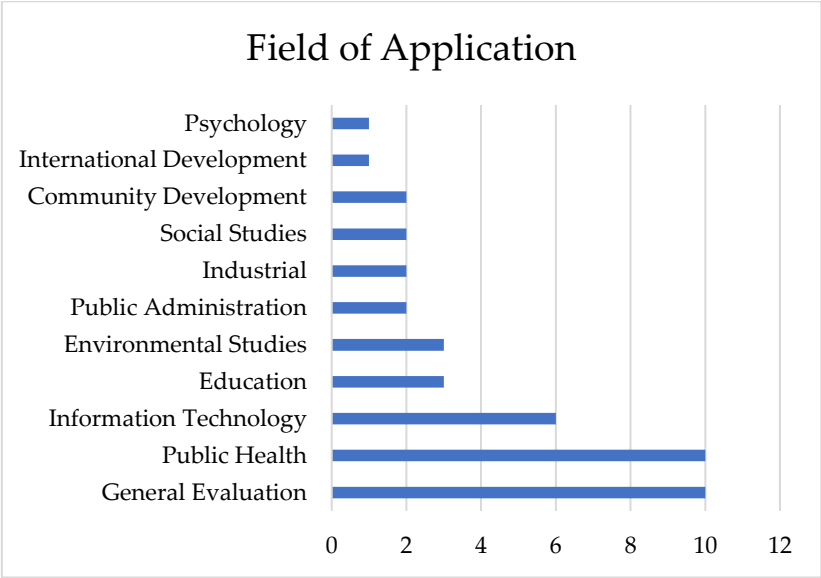


Figure 14: Distribution of Reviewed Papers by Field of Application

Not surprisingly, the two domains of General Evaluation and Public Health stand out prominently, as evaluation science has long provided structured approaches for assessing outcomes and impacts, while public health, characterized by complex systems, multi-level interventions, and strong traditions in causal inference, has often served as a fertile ground for modelling techniques that aim to link inputs to measurable societal results.

Following this, a significant proportion of contributions stem from the Information Technology sector, often focusing on modelling digital interventions, system dynamics in cyber-physical systems, or the interaction between infrastructure and policy mechanisms. Interestingly, Education and Environmental Studies also appear as active fields, both of which share a tradition of systemic reasoning and stakeholder-centric planning, offering useful methodological overlaps for sustainability-related research.

The remainder of the literature is more scattered across Public Administration, Industrial Systems, Community Development, Social Sciences, and a few isolated

instances from International Development and Psychology. While smaller in volume, these contributions introduce context-specific adaptations and practical case insights.

Overall, the diversity of fields reinforces the cross-sectoral relevance of the selected models, but also reveals a relative underrepresentation of sustainability-specific applications, particularly in the context of digital transformation.

2.2.5. Findings

Across the set of 42 identified papers, twelve modelling approaches emerged as the most relevant, robust, and recurring, as either used consistently in multiple papers, recognized in methodological guidelines, or widely adopted across disciplines dealing with complexity, impact evaluation, or system change. These models stood out not only for their frequency of application, but also for the alignment between their modelling logic and the analytical needs defined in this research.

2.2.5.1. Models' Categorization

Each model was naturally assigned to one of the four methodological families introduced earlier, based on the dominant structural logic it reflects and supported by academic literature:

- The Logic Model and Theory of Change were grouped under Theory-Based Models, as they represent sequential or conditional pathways of change built on underlying assumptions. Their classification aligns with Weiss and Connell & Kubisch, who describe such tools as foundational to theory-driven evaluation strategies [112, 125].
- The Causal Loop Diagram, Stock and Flow Diagram, Group Model Building (GMB), and Fuzzy Cognitive Maps (FCM) were classified as System Dynamics and Participatory Models because, despite structural variation, these tools all emphasize feedback loops, non-linearity, and dynamic system behaviour—core principles in Sterman's system dynamics framework [123]. As a delicate note, GMB and FCM were included here because, despite their participatory or cognitive extensions, their primary analytical logic remains rooted in dynamic system behaviour modelling. GMB, in fact, originates directly from the system dynamics tradition, using participatory processes to co-create causal loop or stock-and-flow diagrams, which are then used to simulate system behaviour [116]. FCMs, instead, although involving the use of stakeholder input to define concept structures, have the core of their simulation processes following principles of weighted feedback loops and iterative state updates, which structurally resemble dynamic systems over time [115, 135].
- The Causal Pathway Diagram and Structural Equation Modelling (SEM) were grouped under Structural and Statistical Causal Models, given their shared

focus on formal causal structure, hypothesis testing, and empirical validation. This classification draws from Pearl's theory of structural causal models, which underpins many contemporary approaches to statistical causal inference [113].

- The Input-Output-Outcome-Impact (IOOI) Model, RE-AIM Framework, Analytic Hierarchy Process (AHP), and Analytic Network Process (ANP) were ultimately included under Evaluation and Prioritization Frameworks. While differing in structure, these tools all converge in their use for multi-criteria assessment, impact evaluation, and decision support in complex environments. Their categorization is supported by Saaty for AHP, and by Belton & Stewart for broader multi-criteria decision-making methods [149, 114].

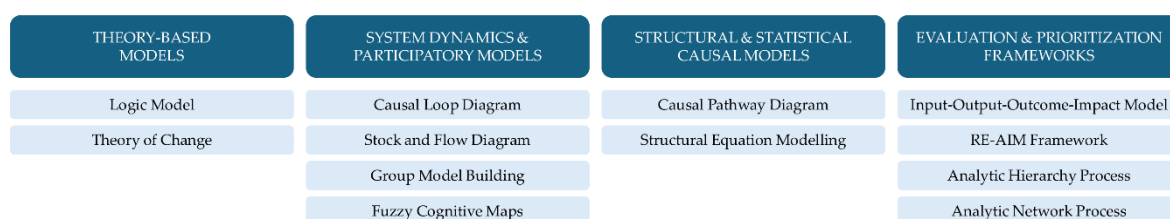


Figure 15: Models Classification into Families

Naturally, it is challenging to assign each model unequivocally to a single methodological family, as several approaches exhibit hybrid characteristics that span multiple logics and could potentially justify different allocations – as for example already highlighted in the case of Group Model Building (GMB) and Fuzzy Cognitive Maps (FCM). However, for the purposes of this review, and for facilitating a coherent comparison across models while still acknowledging their interdisciplinary and integrative nature, each model was assigned to the family that most closely reflects its core structural logic and dominant analytical function.

Taken together, these twelve models provide a robust conceptual foundation for the classification and comparative review that follows, supporting a deeper understanding of how digital enablers interact with sustainability-related systems.

2.2.5.2. Classification Process

To enable a systematic comparison of the selected modelling approaches, an Excel-based classification framework was developed, designed to ensure consistency across the analysis and to make the diverse models comparable along a shared set of analytical dimensions. Given the variety in structure, orientation, and intended use of the selected models, this step was essential to extract insights not only from each individual approach, but also from the broader methodological patterns that emerged across them.

Each model was catalogued using a dedicated row in the Excel file, and assessed according to a set of standardized classification variables, which reflect both technical properties and functional considerations. These variables were chosen to align with the analytical needs of the thesis and include:

- Model Name and Template: Identification of the model and representation of its general, most common outline
- Category: Association with one of the four methodological families previously mentioned
- Purpose / Use Case: Summary of the typical functions or intended applications of the model, such as strategic planning, evaluation, simulation, or prioritization
- Field(s) of Application: List of disciplines or domains where the model has been or is typically applied, including sectors such like public health, digital governance, and ESG reporting
- Structure: Description of the model's structural logic, specifying the way relationships are represented and the presence of eventually linear, recursive, hierarchical, network-based, or feedback-oriented links
- Key Components: Enumeration of the models' essential building blocks, including inputs, outputs, outcomes, activities, feedback loops, latent variables, conditions, etc.
- Causality Representation: Assessment of how causality is structured – whether linear, conditional, probabilistic, recursive, or fuzzy – and whether assumptions are explicit or inferred
- Level of Quantification: Analysis of the degree to which models support qualitative, semi-quantitative, or fully quantitative reasoning and data integration
- Visualization Format: Description of the graphical or diagrammatic style used to communicate the model, such as flowcharts, path diagrams, feedback loops, matrices, or hierarchical trees

By organizing the models across these dimensions, the classification enabled both horizontal comparison (across models) and vertical synthesis (within families), offering a clear basis for the structured overview presented in the next section. Moreover, it provided a functional lens through which each model's suitability for analysing digital-sustainability interactions could be interpreted and discussed.

2.2.5.3. Models' Overview

To complete the methodological review, this section presents a comparative overview of the twelve selected models, grouped according to the four methodological families introduced earlier. Each subsection begins with a brief explanation of the family's core

logic and orientation, followed by narrative profiles describing the structure, application, and analytical characteristics of each model.

The classification is designed to ensure that all relevant dimensions of each model are considered, particularly those that influence their potential suitability for the aims of this thesis. Specifically, it enables a clearer understanding of how each approach may support the analysis of digitalization's impact on sustainability, by revealing differences in how causal logic, feedback, prioritization, and quantification are conceptualized and operationalized.

Theory-Based Models

Models falling under this classification are designed to articulate how change is expected to occur in a structured and interpretable format. They typically follow a linear or conditional layout grounded in explicit assumptions, making them especially valuable for strategy design, impact mapping, and stakeholder communication.

- **Logic Model:** It is a foundational planning and evaluation tool designed to visually map the linear sequence linking program resources, activities, and outputs to short- and long-term outcomes [117, 118]. Due to its ability to provide a common and readable framework for stakeholders, it has been widely applied in public policy, healthcare, education, and corporate sustainability initiatives, including ESG reporting [117, 118, 119]. The structure is inherently sequential, with components flowing from left to right, beginning with inputs and concluding with broader impacts. Each stage (inputs, activities, outputs, outcomes, impacts) is represented in aggregated form, without giving relevance to single variables, and is assumed to causally lead to the next, without loops or contextual variability [117, 118]. While largely qualitative in its initial conception, the Logic Model can be enriched with KPIs and indicators for performance monitoring, making it a versatile tool across sectors [117, 119]. Visualization is typically achieved through flowcharts or structured tables with annotated components, eventually including colour coding and assumptions specification.
- **Theory of Change:** It advances the linear logic of the previous model by explicitly working backward from long-term goals to identify necessary preconditions, interventions, and assumptions [120, 121, 124]. It is used extensively in strategic planning and evaluation for international development, systems innovation, and sustainability initiatives [120, 122, 124], and is increasingly adopted in ESG strategy corporate planning where multi-layered impacts and stakeholder interdependence are central. Unlike the Logic Model, its structure is majorly but not necessarily linear, potentially incorporating multiple causal pathways, conditional branches, and contextual dependencies [122, 125]. It provides a more theory-driven, adaptable narrative of how change

is expected to unfold and why it is believed to work, allowing for iterative revision as learning accumulates [120, 121, 122]. Its structure typically includes a long-term impact, a sequence of intermediate outcomes, targeted interventions, necessary inputs, and explicit assumptions [121, 122, 124], enhancing transparency and supporting critical reflection. While mainly and mostly qualitative, the model can be enriched with indicators or KPIs to support monitoring and evaluation [120, 121, 122]. It is usually represented as a flow diagram, annotated with narrative explanations and causal arrows, but the level of detail varies depending on purpose [121, 122].

	PURPOSE	FIELD OF APPLICATION	CAUSAL STRUCTURE	QUANTIFICATION LEVEL	KEY ELEMENTS	VISUALIZATION FORMAT
LOGIC MODEL	Planning & Evaluation	Public Policy, Healthcare, Education, ESG	Linear and Sequential	Qualitative (with KPIs)	Inputs, Activities, Outputs, Outcomes, Impacts	Flowchart / Structured Table
THEORY OF CHANGE	Strategic Design & Impact Mapping	International Development, Systems Innovation, ESG Strategy	Conditional and Sequential	Qualitative (with KPIs)	Preconditions, Interventions, Outcomes, Assumptions	Flow Diagram with Causal Arrow

Table 1: Classification of Theory-Based Models

System Dynamics and Participatory Models

This family of models is grounded in the principles of systems thinking and is designed to capture the dynamic behaviour of complex systems over time, emphasizing feedback loops, time delays, non-linear interactions, and, in many cases, collaborative mapping with stakeholders. Whether used to simulate quantitative dynamics or facilitate qualitative understanding, their goal is to explain how outcomes emerge from the interaction of multiple variables within an evolving system, helping to uncover leverage points, anticipate unintended consequences, and co-create system-level insights.

- **Causal Loop Diagram (CLD):** This model departs from sequential representations by illustrating the feedback structure of complex systems through cause-and-effect relationships among variables [130, 131]. It is widely used in fields such as sustainability science, climate change, urban planning, public health and, more in generale, all those domains where system behaviour emerges from non-linear interdependencies and adaptive responses [130, 131, 132]. Rather than following a linear flow, CLDs map circular causality using loops that can either reinforce or balance changes in the system over time [130, 131], connecting variables through directional arrows marked with polarity signs (+/-) used to indicate whether a change in one term strengthens or dampens another [130]. While typically qualitative, CLDs can be expanded into full simulation models—especially when integrated with stock-and-flow

diagrams—to support dynamic scenario analysis and long-term forecasting [131, 132]. Their graphical format typically includes labelled nodes, feedback loops, and annotations such as “R” for reinforcing and “B” for balancing effects, often complemented by time delay indicators (| |) to show lags between cause and effect [130, 131].

- Stock and Flow Diagram:** This model extends the logic of system dynamics by simulating how resources accumulate or change over time, capturing both the structure and behaviour of dynamic systems [139, 140]. It is widely applied in environmental modelling, public health, economics, and infrastructure planning, contexts where feedback, time delays, and nonlinear relationships are critical [139, 140]. Built on the system dynamics paradigm, SFDs quantify variables using mathematical equations, linking stocks and flows through auxiliary variables and feedback loops that govern system evolution [139]. Causality is fully dynamic and embedded in recursive relationships, allowing for the simulation of long-term behaviours, scenario testing, and impact assessments. SFDs are often viewed as the quantitative counterpart of Causal Loop Diagrams, transforming conceptual logic into computable models [139, 140]. Their structure includes boxes (stocks), double-lined arrows (flows), and valves, usually constructed with specialized software like Vensim or Stella [139, 140].
- Group Model Building (GMB):** This participatory approach focuses on constructing causal models collaboratively with stakeholders, typically in the form of causal loop or stock-and-flow diagrams [153, 154]. It is widely used in multi-actor environments such as public health, environmental management, regional planning, and sustainability transitions, and in all contexts where trust, dialogue, and shared understanding are critical to success [153, 154]. GMB sessions are usually conducted through structured workshops in which participants collectively define problems, map variables, identify feedbacks, and propose interventions [153]. Causality is explicitly mapped in real time with stakeholder input, offering both a shared conceptual framework and a basis for further simulation and policy analysis [154]. While initially qualitative, models produced through GMB can evolve into quantitative tools when supported by sufficient data and consensus. Typically converging into CLDs or Stock-and-Flow Diagrams, final representations often include annotated causal diagrams, clustered variables, and time-delayed links, built using both manual and digital tools [153, 154].
- Fuzzy Cognitive Map (FCM):** Designed to represent and simulate complex systems using fuzzy logic, it aims to capture the strength and uncertainty of relationships among variables [133, 135]. FCMs are especially valuable in contexts where expert knowledge is available but quantitative data is limited, such as environmental management, policy modelling, and sustainability planning [133, 135]. The typical structure consists of directed graphs in which

nodes represent system concepts and edges are weighted to reflect the direction and intensity of influence. Causality, on the other side, is explicit, weighted, and inherently fuzzy, with each link reflecting a graded rather than binary effect and consequently allowing the model to incorporate feedback, cyclical processes, and uncertain or evolving relationships [133, 135]. Model behaviour is simulated through matrix algebra, while scenario testing and exploration of policy alternatives is enabled under dynamic, uncertain conditions. While FCMs are semi-quantitative, with weights typically derived from expert input, their analytical power lies in their ability to handle nonlinearity, adaptivity, and systemic complexity. Visually, they are presented as network diagrams with directional arrows, influence weights, and sometimes supported by simulation curves, heatmaps, or decision tables [133, 135].

	PURPOSE	FIELD OF APPLICATION	CAUSAL STRUCTURE	QUANTIFICATION LEVEL	KEY ELEMENTS	VISUALIZATION FORMAT
CAUSAL LOOP DIAGRAM	Feedback Mapping & System Insight	Sustainability, Climate, Health, Urban Planning	Circular Feedback Loops	Qualitative	Variables, Arrows, Polarity Signs (+/-), Loops	Loop Diagram with R/B Indicators
STOCK AND FLOW DIAGRAM	System Simulation	Environment, Economics, Infrastructure Planning	Dynamic, Recursive Feedback	Quantitative	Stocks, Flow, Valves, Equations, Auxiliaries	Boxes and Arrows (Vensim, Stella)
GROUP MODEL BUILDING	Participatory Model Creation	Public Health, Regional Planning, Sustainability	Stakeholder-Mapped Causality	Qualitative	Variables, Feedbacks, Interventions, Consensus	Live-Built CLDs/SFDs with Annotations
FUZZY COGNITIVE MAP	Simulation under Uncertainty	Policy, Environment, Sustainability Strategy	Weighted, Fuzzy Feedback	Semi-Quantitative	Nodes, Weighted Edges, Feedback, Influence Weights	Network Diagram with Arrows and Matrices

Table 2: Classification of System Dynamics and Participatory Models

Structural and Statistical Causal Models

These models are grounded in formal causal reasoning and statistical estimation, aiming to empirically validate the relationships between variables within complex systems. Unlike conceptual or simulation-based approaches, they rely on observable data, latent constructs, and mathematical formulations, and test hypotheses about how multiple factors interact, mediate, or moderate one another. Particularly well suited for empirical evaluation, they enable researchers to quantify both direct and indirect effects, assess model fit, and support causal inference in systems where interdependencies are complex and multidimensional.

- **Causal Pathway Diagram:** This model is designed to trace and clarify how interventions lead to outcomes through a sequence of observable, intermediate steps [126, 127]. Commonly used in fields such as public health, international development, and ESG reporting, it supports hypothesis testing, attribution

analysis, and data collection by visually organizing cause-and-effect chains [126, 127] in a linear or semi-linear structure that typically begins with inputs and then progresses with implementation strategies, activities, outputs, proximal and distal outcomes. It may also include moderating or preconditioning variables that influence these relationships [126, 128]. Causality is explicit and hypothesis-driven, allowing each connection to be tested through indicators, correlation, or regression coefficients, and, while it does not inherently model feedback, the diagram can incorporate conditional or branching logic to reflect complex or probabilistic causality [126, 127]. Its analytical orientation strongly supports quantitative analysis [126, 128] and it is visually represented as a horizontal or vertical flowchart annotated with metrics, assumptions, or confidence levels [127]. Importantly, it is frequently used as a foundation for Structural Equation Models (SEM) [126].

- **Structural Equation Modeling (SEM):** It is a quantitative method used to analyse complex causal relationships among observed and latent variables by integrating factor analysis with multiple regression in a unified framework [141]. It is widely applied in fields such as psychology, public health, education, and sustainability, especially when investigating how indirect and mediated effects influence outcomes [141]. The model includes both a measurement and a structural component, allowing estimation of direct, indirect, and total effects [141], and is fully quantitative, typically based on large datasets and covariance matrices that undergo stages such as model specification, parameter estimation, and goodness-of-fit testing [141, 142]. Causality is explicit and testable, with the model capable of representing recursive, bidirectional, or moderated relationships, while visualizations take the form of path diagrams with ovals (latent variables), rectangles (observed variables), and directional arrows [141].

	PURPOSE	FIELD OF APPLICATION	CAUSAL STRUCTURE	QUANTIFICATION LEVEL	KEY ELEMENTS	VISUALIZATION FORMAT
CAUSAL PATHWAY DIAGRAM	Attribution & Hypothesis Testing	Public Health, Development, ESG Reporting	Linear or Conditional, No Feedback	Quantitative	Inputs, Activities, Outcomes, Moderators, Indicators	Flowchart with Metrics and Assumptions
STRUCTURAL EQUATION MODELING	Causal Estimation with Latent Variables	Psychology, Health, Education, Sustainability	Recursive, Bidirectional	Fully Quantitative	Latent & Observed Variables, Coefficients, Covariance Matrices	Path Diagram (Ovals, Rectangles, Arrows)

Table 3: Classification of Structural and Statistical Causal Models

Evaluation and Prioritization Frameworks

This family encompasses frameworks designed to support structured decision-making, impact evaluation, and resource allocation in contexts involving multiple objectives, stakeholder interests, and complex trade-offs. Unlike models focused solely

on causal mapping or system behaviour, these approaches are especially useful when outcomes must be weighed, compared, or justified across diverse sustainability dimensions and in absence of objective, universally acceptable criteria. Whether organizing performance indicators, assessing implementation feasibility, or guiding strategic priorities, these models help translate complexity into actionable criteria that meet stakeholders' requirements, making them particularly relevant in ESG planning and digitally enabled sustainability strategies.

- Input-Output-Outcome-Impact Model:** This model offers a structured yet simplified representation of how a resource investment unfolds into measurable societal or environmental impact, organizing change into a sequential chain of inputs, outputs, outcomes, and impacts [143]. Commonly used in program evaluation, development initiatives, and ESG reporting, the IOOI model has found growing relevance in smart infrastructure projects where technical interventions must be logically linked to strategic goals [144]. The structure assumes a linear causal logic in which each stage builds on the preceding one: from resources invested to activities delivered, immediate changes achieved, and broader long-term effects realized [143, 144, 145]. While the model does not necessarily require empirical validation of each link, it emphasizes strategic clarity and accountability by encouraging performance indicators and monitoring targets at every step [144]. It accommodates both qualitative reasoning and quantitative scorecards, often supporting mixed-methods evaluation and alignment with ESG standards or SDGs [143, 145]. Visually, the model is typically presented as a horizontal or vertical flow of labelled boxes and arrows, sometimes annotated with indicators, assumptions, or responsibilities as it often happens in theory-based models [143, 144].
- RE-AIM Framework:** Originally developed to evaluate the real-world impact of public health interventions, with a particular emphasis on both outcomes and implementation quality [146, 148], it has since been adapted to a wide range of scalable interventions, including digital transformation and sustainability programs [146, 147]. RE-AIM is structured around five core dimensions—Reach, Effectiveness, Adoption, Implementation, and Maintenance—which together provide a multidimensional picture of performance at both individual and organizational levels [146]. Unlike linear causal models, RE-AIM does not map a sequential pathway of change, but rather encourages evaluation across complementary domains, making it especially suitable when external validity and real-world applicability are critical [146, 148]. It can be applied using quantitative indicators, qualitative insights, or mixed methods, and is often integrated into broader scorecards or decision-making tools [147]. Visually, instead, it is typically displayed as a matrix, dashboard, or radar-style diagram populated with data for each domain [147].

- **Analytic Hierarchy Process (AHP):** It is a structured decision-making method designed to break down complex problems into a hierarchy of goals, criteria, and alternatives, assigning weights to each element through expert judgment [149, 150]. It is extensively used in ESG prioritization, sustainability planning, and infrastructure strategy, especially when both qualitative and quantitative dimensions must be considered [149]. Decision-makers conduct pairwise comparisons at each level of the hierarchy to derive priority scores, which are then aggregated using mathematical techniques, like eigenvalue computation, to obtain comprehensive scores [150]. While not a causal model per se, AHP supports informed weighting within causal frameworks and helps clarify trade-offs among competing goals, allowing stakeholders to give more importance to those objectives that are most relevant to them [149]. Although not including any computation in terms of KPIs or measurements, the process converts qualitative preferences into numerical values on a 1–9 scale, ultimately organizing outputs into weight tables or ranked alternatives [149, 150]. It is usually visualized as a tree diagram combined with comparison matrices to represent preferences and consistency checks [149].
- **Analytic Network Process (ANP):** Conceptually similar but not entirely, this model extends the logic of AHP to account for feedback loops, interdependencies, and non-hierarchical structures, offering a more flexible framework for multi-criteria prioritization in complex systems [151, 152]. It is especially useful in sustainability planning, ESG trade-off analysis, and strategic decision-making contexts, where elements influence each other reciprocally and is difficult to trace back all relationships to linear causal links [151]. The model is structured as an interconnected network of clusters and nodes, where influence weights are derived from expert pairwise comparisons and synthesized via a supermatrix that aggregates all relationships [152]. Like AHP, it relies on a 1–9 scale for pairwise comparisons and generates weighted priorities suitable for scenario analysis and policy evaluation; however, unlike AHP, it allows for mutual influence among elements, becoming particularly well-suited for capturing circular dynamics and stakeholder interdependencies [151, 152]. Outputs are typically presented as network diagrams accompanied by supermatrices, and its complex modelling is usually enabled by software tools like SuperDecisions [152].

	PURPOSE	FIELD OF APPLICATION	CAUSAL STRUCTURE	QUANTIFICATION LEVEL	KEY ELEMENTS	VISUALIZATION FORMAT
IOOI MODEL	Strategic Planning & Impact Tracking	Program Evaluation, ESG Reporting, Infrastructure	Linear	Mixed (Qualitative & Quantitative)	Inputs, Outputs, Outcomes, Impacts, Indicators	Flowchart with Boxes, Arrows, Annotations
RE-AIM FRAMEWORK	Implementation & Outcome Evaluation	Public Health, Sustainability, Digital Programs	Non-linear, Multidimensional	Mixed (Qualitative & Quantitative)	Reach, Effectiveness, Adoption, Implementation, Maintenance	Matrix, Dashboard, Radar Diagram
ANALYTIC HIERARCHY PROCESS	Prioritization & Decision-Making	ESG Planning, Infrastructure, Multi-Criteria Evaluation	Hierarchical, No Feedback	Semi-Quantitative	Goals, Criteria, Alternatives, Pairwise Weights	Tree Diagram with Comparison Matrices
ANALYTIC NETWORK PROCESS	Interdependent Prioritization	ESG Trade-Offs, Strategic Decisions	Networked with Feedback Loops	Semi-Quantitative	Clusters, Nodes, Pairwise Weights, Supermatrix	Network Diagram with Supermatrix

Table 4: Classification of Evaluation and Prioritization Frameworks

2.2.5.4. Summary of Findings

The review of the twelve modelling approaches, grouped into the previously mentioned four methodological families, highlighted the diversity and complementarity of tools available for exploring the digital–sustainability nexus.

- **Theory-Based Models** provide structured and often visual representations of how planned actions are expected to lead to desired sustainability outcomes, being best suited for planning, evaluation, and strategic reasoning, especially in multi-stakeholder settings. These models excel in transparency and logical consistency, typically following a clear causal logic that facilitates communication and accountability, but offer limited support for dynamic feedback, recursive influence, or bidirectional relationships, oversimplifying reality. Their granularity is often coarse, with variables grouped into broad stages (e.g., inputs, outputs), which can hinder precise causal traceability and make it difficult to properly attribute responsibilities and credits. While models like the Theory of Change allow the inclusion of KPIs and assumptions, they do not support rigorous quantification or nuanced differentiation among variable types or causal strengths, being particularly effective at articulating strategic narratives and expected pathways but falling short in terms of simulation or empirical testing.
- **System Dynamics and Participatory Models** are uniquely capable of capturing feedback loops, time delays, and emergent behaviours in complex systems, shining when it comes to mapping real-world interdependencies and identifying unintended consequences or leverage points, especially under uncertainty. Their participatory nature (as in GMB) also fosters stakeholder

alignment and shared understanding, which is extremely valuable in multipart systems that often require a portion of subjectivity and original reasoning. However, their inherent complexity and emphasis on system-wide behaviour often lead to trade-offs in structural clarity and hierarchical consistency, hindering the possibility to properly interpretate what displayed. Variables may recur across loops, making it harder to isolate their distinct roles, and atomic representation is often lost in aggregated nodes. Moreover, although simulation tools like Stock and Flow Diagrams enable precise quantification, these models are not naturally aligned with one-directional or layered causality, being better at describing circular reciprocal behaviours than providing a clear trace from input to impact.

- **Structural and Statistical Causal Models** offer the most rigorous foundation for testing hypotheses, quantifying relationships, and validating complex causal pathways through empirical data. Their strength lies in their ability to decompose total effects into direct and indirect components, to include mediators or moderators, and to statistically evaluate model fit, which all makes them particularly valuable for detecting subtle interactions and confirming causal assumptions. However, the formality of these models often comes at the expense of interpretability: they are difficult to communicate visually, and their diagrams, while precise, do not always reflect intuitive system logic or stakeholder understanding. Furthermore, they tend to prioritize statistical power over structural comprehensiveness, limiting their suitability for exploratory or participatory design. These models are strong on quantification and categorization of effects, but less suitable for projects or analyses requiring visual clarity, bottom-up causality, or clearly layered representations.
- **Evaluation and Prioritization Frameworks** are particularly valuable in contexts requiring structured comparisons, multi-criteria trade-off evaluation, or stakeholder-driven prioritization. Tools like AHP and ANP allow the assignment of weights, pairwise comparisons, and influence scoring even in the absence of quantifiable data, while IOOI and RE-AIM structures support accountability and impact tracking through the systematic use of indicators. These models excel at integrating expert judgement and qualitative reasoning with structured outputs, and often include indicator-based monitoring systems that support decision-making. However, they are not naturally causal in orientation, failing to capture the actual relationships that lead from original inputs to final outcomes through a series of intermediary steps. While well suited for categorizing impact and assigning priorities, their abstract representation and lack of directional granularity make them insufficient for tracing digital enablers' influence across multi-tiered sustainability pathways.

Together, these models reflect a methodological landscape that is well-developed in several domains but remains fragmented when applied to the challenges of digital

transformation and its implications for ESG performance. While robust tools are available for planning, simulation, prioritization, and causal inference, no single model fully integrates all these capabilities. As a result, practitioners are often required to combine or adapt existing approaches to address the interdisciplinary and evolving demands of digitally enabled sustainability strategies.

2.2.6. Limitations

While this chapter has aimed to provide a comprehensive and structured review of modelling approaches suitable for assessing the impact of digitalization on sustainability, several limitations must be acknowledged.

First, the selection of models, though grounded in defined analytical criteria and supported by extensive literature, is not exhaustive. The chosen set reflects a targeted effort to balance conceptual diversity with practical relevance, but necessarily omits other potentially valuable approaches, particularly the emerging or hybrid ones that may not yet be widely codified in academic literature. Similarly, models from adjacent disciplines such as behavioural economics, network theory, or machine learning were excluded, even though they may offer complementary perspectives on system dynamics or decision-making.

Second, while the classification into four methodological families provided a useful structure for comparative analysis, it inevitably simplified the complex and often overlapping models' characteristics. Many of the discussed approaches possess hybrid features that span multiple categories, and their real-world use may not always align neatly with the theoretical family to which they are assigned. This simplification, therefore, although deliberate and intentionally driven by the will to simplify and schematize dissertation, may have obscured the adaptability and evolving nature of many methods.

Moreover, the review focused primarily on the structural, analytical, and functional dimensions of each model, rather than their implementation challenges or organizational feasibility. Factors such as required expertise, data availability, software dependencies, stakeholder involvement, and institutional readiness were not systematically addressed, yet they significantly influence the choice and successful application of a modelling approach in real-world contexts.

Finally, it must be remembered that the analysis is constrained by the availability and quality of secondary sources as, while care was taken to ensure academic robustness, the descriptions, visualizations, and applications of some models relied on interpretations from case studies, toolkits, or institutional guides rather than peer-reviewed empirical validations. As a result, the comparative assessment may reflect idealized versions of each model rather than the full spectrum of their practical use.

However, despite these limitations, the chapter sufficiently describe the current methodological landscape and offers a solid foundation for the development of an integrated modelling framework that is better aligned with the complexities of digital-sustainability interactions.

2.3. Identification of Research Gaps

The analysis of the existing literature has highlighted an increasing academic and institutional interest in sustainability assessment and the role of digital technologies in supporting corporate ESG performance. However, despite this growing attention, several gaps remain unresolved both at a methodological and conceptual level, leaving space for further contributions.

One of the most recurrent issues across the examined studies lies in the proliferation of KPIs and the absence of clear guidelines on how to select, prioritize, and apply them within specific organizational contexts. While many papers contribute comprehensive lists of sustainability indicators, they often fall short in offering structured approaches for their adaptation to different sectors, operational realities, or reporting obligations. Exacerbated by even more confusing and vague regulatory directives, this lack of standardization results in incoherent assessments and undermines the comparability of sustainability efforts across companies and industries.

Moreover, current practices in sustainability reporting are still predominantly based on rigid, manual processes, where KPIs are computed through static spreadsheets and averaged approximations. This outdated approach not only delays the identification of inefficiencies but also prevents the timely adjustment of strategies in response to performance deviations. Indeed, despite the recognized potential of real-time data gathering and digital monitoring systems, literature and practice continue to show a limited adoption of such technologies in concrete assessment frameworks, with most of the existing tools failing to exploit the opportunities offered by digitalization to transform sustainability reporting into a dynamic, automated, and decision-oriented process.

Another persistent issue concerns the imbalance in how the three ESG pillars are represented because, while the environmental dimension benefits from a relatively high degree of methodological maturity and regulatory support, the social and governance aspects remain underdeveloped, especially in terms of well-defined, quantifiable indicators. This underrepresentation is particularly evident in the literature's tendency to either subsume governance within broader economic considerations or to rely on subjective and qualitative metrics for assessing social impacts. As a result, many companies still struggle to capture the full scope of their

sustainability performance, and often lack the tools to address internal aspects such as employee well-being, ethical governance, or transparency in data handling.

Beyond these issues related to KPI definition and usage, a second cluster of research gaps concerns the evaluation of how digital solutions concretely impact sustainability performance. Indeed, while numerous papers recognize the theoretical potential of technologies like IoT, artificial intelligence, and blockchain to support more sustainable operations, most contributions are either conceptual or limited to case-specific insights, not allowing a full generalization of results. There is a notable lack of integrative models capable of tracing the mechanisms through which digital enablers influence ESG outcomes, and only few studies succeed in representing how operational, organizational, and technological levers mediate the relationship between digital investments and sustainability improvements across all three dimensions. To further wide the gap, a scarcity of analytical models that transcend specific sectors or geographies and allow generalization across different contexts and global companies.

Although several methodological traditions – ranging from theory-based models to system dynamics and statistical causal models – have been applied to sustainability analysis, there remains a notable absence of comprehensive frameworks capable of explicitly mapping the causal pathways between digital interventions and sustainability outcomes. While existing models offer valuable contributions in terms of strategic planning, dynamic simulation, or performance evaluation, they tend to operate in isolation, each addressing only a fragment of the broader transformation process. As a result, they often fail to provide a structured understanding of how the implementation of digital technologies concretely influences sustainability performance, particularly when such effects are indirect, mediated, or context-dependent. In a fast-changing moment led by the power of digitalization, there is a growing need for integrated modelling approaches that can go beyond correlation or high-level assumptions to instead offer a transparent, evidence-based representation of the mechanisms through which tech tools affect environmental, social, and governance dimensions. Without such models, in fact, it remains difficult to assess the real efficacy of digitalization efforts and to guide decision-makers in designing technology strategies that genuinely contribute to long-term sustainability goals.

3 Objectives and Research Method

3.1. Introduction

The purpose of this chapter is to outline the core research objectives that guided the thesis, and to describe the methodological approaches adopted to address them. Anchored in the gaps identified within the literature, the work follows a sequential logic aimed at addressing three interconnected challenges: enabling structured and context-sensitive sustainability assessment, understanding the causal mechanisms through which digital solutions impact ESG outcomes, and ensuring that the resulting model can be generalized and applied across diverse contexts. Each research question corresponds to a specific analytical effort and is supported by a dedicated methodological path, together constituting the core and reasons why of the study.

3.2. Research Objectives

3.2.1. O1: Standardizing Sustainability Assessment

As emerged from the literature review, organizations increasingly face the challenge of assessing their sustainability performance in a way that is both rigorous and adaptable to their specific context, with current practices often undermined by a lack of consistency in indicator selection, limited comparability across industries, and insufficient alignment with regulatory and strategic objectives. Sustainability reporting, though widespread, frequently relies on fragmented sets of KPIs, many of which are either too generic to guide meaningful action or too specific to be applicable across different organizational settings, while the unbalanced attention given to environmental indicators often leaves social and governance dimensions underrepresented or poorly quantified.

The first objective of this research was therefore to develop a structured and hierarchically organized framework for sustainability assessment, capable of ensuring coherence, comparability, and comprehensive coverage across all ESG dimensions while supporting companies in overcoming current limitations in reporting practices. Designed to integrate regulatory expectations, academic contributions, and corporate best practices, the framework enables users to identify relevant KPIs based on the specific ESG dimensions they intend to monitor, while ensuring transparency,

comparability, and potential for future automation. Fundamentally, the question that moved and drove the first part of the research is:

How can a structured, hierarchical KPI framework be developed to standardize sustainability assessment across companies and industries?

3.2.1.1. M1: Framework Population and KPIs Structuring

To address the first research question, the work adopted a hybrid methodology combining internal reference structures with an extensive external review of sustainability indicators. In particular, the framework foundation was provided by an existing ESG classification system developed by the Digital & Sustainable Observatory of Politecnico di Milano, within which the entire thesis was conducted in close collaboration. Characterized by a three-level hierarchical structure that distinguishes between environmental, social, and governance dimensions, articulating them into increasingly specific subcategories [218], the already defined framework was taken as input and progressively refined throughout the whole process. Its population, on the other hand, was carried out through a systematic selection and integration of KPIs sourced from academic literature, regulatory frameworks (such as the ESRS and SDGs), corporate sustainability reports, and sector-specific standards. In total, several hundred KPIs were reviewed, and a curated set was selected to reflect both established metrics and emerging ones that capture the evolving nature of sustainability challenges. Then, the same selected indicators were further classified along multiple dimensions, including their correspondence to sustainability subcategories, type of measurement (quantitative or qualitative), and degree of methodological robustness. In general, special attention was given to the balanced representation of all three ESG pillars and the overarching goal was to construct a hierarchically organized framework capable of guiding companies in the identification of relevant and measurable indicators aligned with both internal objectives and external expectations.

The resulting tool is not a static checklist but a flexible and scalable framework designed to support organizations in structuring their sustainability assessment processes while enabling strategic decision-making, comparability, and eventual integration with digital monitoring systems.

3.2.2. O2: Evaluating the Impact of Digital Solutions

As highlighted in the previous chapter, while digital technologies are increasingly recognized as key enablers of sustainable transformation, the literature still lacks structured models capable of explicitly tracing how such technologies contribute to improved ESG outcomes. Most existing approaches either focus on qualitative narratives or assess isolated performance indicators, without offering a

comprehensive and causally grounded understanding of the transformation process. Moreover, even when digitalization is cited as a driver of sustainability, the underlying mechanisms—how and why certain technologies produce measurable impacts—are rarely made explicit or replicable.

Finally, but not less importantly, when digital-sustainability interactions are discussed in academic or professional contexts, they are often framed through descriptive case studies or conceptual discussions that remain largely narrative in nature. Rarely do such contributions provide concrete, quantifiable evidence of impact through the use of specific KPIs, nor do they adopt a standardized logic capable of linking digital interventions to multi-dimensional sustainability outcomes. As a result, this lack of quantification further limits the ability to compare findings and conclusions, validate assumptions, or inform decision-making in data-driven environments.

The second objective of this research was therefore to develop a model capable of evaluating the sustainability impact of digital solutions in a structured, transparent, and causally explicit way. The aim was not merely to identify correlations, but to map the intermediate levers, operational shifts, and sustainability outcomes activated by digital interventions, allowing practitioners and researchers to understand and monitor the transformation process in detail. Ultimately, this objective led to the formulation of the second research question:

How can the sustainability impact of digital solutions be evaluated in a structured and causally explicit way?

3.2.2.1. M2: Causal Modelling and ESG Impact Mapping

To address this question, a multilayer causal model was developed, capable of capturing the pathways through which digital technologies influence sustainability performance across environmental, social, and governance dimensions. Crucially, the model was not built in abstraction or based on a single methodological tradition, but developed progressively and in parallel with the analysis of a real-world digital transformation initiative—the Smart Water Management project—whose complexity and documentation richness provided both the empirical basis and the conceptual inspiration for the model's structure.

Rather than adhering rigidly to one modelling school, the framework draws upon and integrates key elements from diverse methodological traditions, including theory-driven planning models, system dynamics, impact assessment frameworks, and logic-based causal mapping. This hybrid construction approach allowed the model to reflect the multidimensionality of sustainability impacts while maintaining internal coherence and practical applicability. The resulting structure is composed of five interconnected layers: (1) digital technologies; (2) tech-enabled capabilities; (3)

operational variables; (4) impact drivers; and (5) ESG KPIs, each properly framed within the sustainability dimensions of the previously developed framework.

For each KPI identified during the case analysis, a causal pathway was reconstructed linking foundational technologies to measurable outcomes, either directly or through intermediate transformations. In addition, each impact was annotated according to its nature (e.g., certain vs. potential, direct vs. indirect) and its strategic role (core objective or unintentional effect), enabling the model to serve not just as an analytical tool, but also as a decision-support framework.

The strength of this model lies precisely in its flexibility, integrative logic, and empirical grounding, as its construction was not imposed upon the case but emerged from it, incorporating tested concepts from multiple approaches into a coherent structure that remains adaptable to other projects and contexts.

3.2.3. O3: Extending Model Applicability

As observed in the literature, many existing sustainability assessment models suffer from limited transferability due to their narrow sectoral focus, rigid variable structures, or lack of methodological transparency. Often tailored to the specific needs of a single industry or use case, these models embed assumptions, variables, and metrics that are difficult to adapt to different organizational or technological contexts and, in some cases, the logic behind the model construction is not clearly documented, making it hard for external actors to replicate or reinterpret the approach. As a consequence, these models' utility in broader applications is severely restricted, preventing meaningful comparison across industries or replication by other researchers and practitioners.

Aware of this issue, the third objective of this research was therefore to transform the developed model from a project-specific framework into a generalizable methodology, capable of guiding the analysis of digital sustainability impacts across diverse contexts. This entailed not only validating the model's internal logic but also formalizing a step-by-step procedure for its application, one that is accessible, reproducible, and adaptable to different technologies, sectors, and organizational settings. Exactly from this ambition, the formulation of the third research question:

How can the proposed model be adapted and reused across different contexts and digital solutions?

3.2.3.1. M3: Method Generalization and Transferability Guidelines

To operationalize the third research question, a formal methodology was developed to enable the scalability and transferability of the causal model beyond the original use

case. This effort involved abstracting the model’s construction logic into a clear, replicable process that others could follow without retracing the entire empirical journey of its original development.

The resulting method is structured into a series of practical and logically ordered steps, covering all phases of application, from the initial understanding of a digital transformation initiative, through the identification of technologies and enabling capabilities, to the selection of KPIs, mapping of causal pathways, and annotation of impacts. Special emphasis was placed on making the method flexible enough to accommodate both quantitative and qualitative indicators, and modular enough to be applied to projects of different scale, scope, and sector.

Each step is enriched with guidance to ensure interpretability and usability, including suggestions for defining variables, structuring layers, minimizing redundancy, and visually encoding key attributes such as impact certainty and strategic relevance. Optional additions, such as stakeholder validation and narrative descriptions, are also proposed to enhance transparency and contextual alignment.

Ultimately, what distinguishes this methodological contribution is its ability to convert a complex and exploratory modelling exercise into a ready-to-use tool, without sacrificing analytical depth. By formalizing the model’s structure and offering a clear implementation pathway, this research aims not only to support immediate reuse but also to contribute to a cumulative scientific approach, where models are not isolated solutions but shared instruments for broader application.

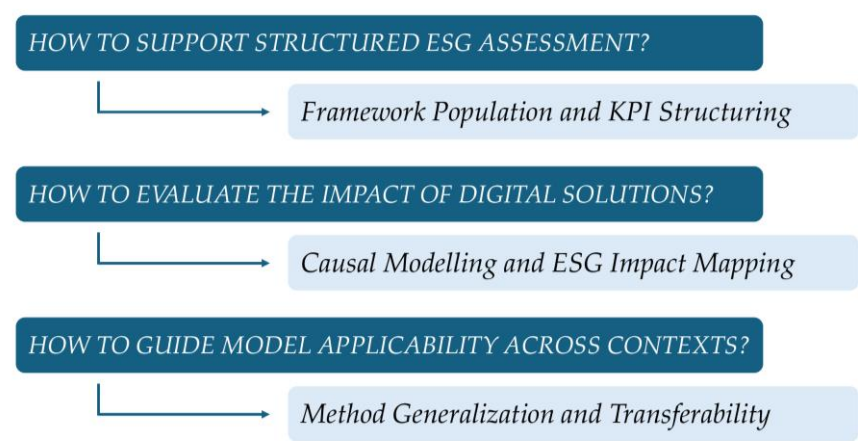


Figure 16: Research Questions and Methodologies

4 Sustainability Assessment Framework

4.1. Introduction

The previous chapter meticulously outlined the current landscape of sustainability assessment within corporate behaviour and highlighted the role of digitalization in the improvement of both monitoring and results achievement. Despite the growing effort of both companies and political agencies to develop more helpful and appropriate tools, the absence of a clear and comprehensive framework for performance evaluation and the still limited exploitation of technologies represent a significant challenge. Therefore, as we transition from the broad exploration of existing literature to the focused methodologies employed in this study, the double-sided goal of the research becomes clear: to establish a comprehensive framework for sustainability assessment, able to cover all possible dimensions, and to determine how technologies can contribute to its integration inside business practices.

The drive towards a holistic sustainability assessment is indeed underscored by the increasing complexity of corporate operations and their extensive impacts on society and the environment as a whole, and traditional models often fall short in capturing these nuanced interactions. While none of the dimensions is actually fully explored, a greater focus has always been put on the environmental one, to the detriment of the governance and social elements which are usually underrepresented. As a result, the few companies that actually work to this end often find themselves with approximative assessments that do not fully account for the spectrum of sustainability impacts that should instead be considered for an all-round evaluation.

Moreover, current regulatory frameworks, while providing a scaffold for sustainability reporting, often lack the specificity or the enforcement rigor necessary to ensure comprehensive and comparable assessments across industries and borders, leading to an extremely various and differentiated landscape.

Acknowledging these limitations, the research aims to develop a framework that not only integrates but also enhances the granularity of sustainability metrics, supporting the adoption of digital tools able to facilitate precise and transparent measurement and reporting. Extracting indicators from a wide array of academic and regulatory sources, the study ensures that each of them is not only relevant but also scrupulously defined and categorizable across different dimensions of sustainability. Moreover, highlighting the alignment of these KPIs with guidelines from European directives and GRI, the study aims to create a synergy between research insights and legislative

frameworks to propel forward the standardization and effectiveness of sustainability assessment. Indeed, the following comprehensive approach is not merely academic in nature but designed with the practical intent of filling the regulatory and conceptual voids that currently exist, paving the way for more effective sustainability governance in the corporate world.

4.2. The Sustainability Framework

The framework employed for the categorization of KPIs, and the consequent proposal of a more than comprehensive set of metrics, was ideated by the Observatory Digital & Sustainable of Politecnico di Milano [218], the research environment within which this thesis was carried out as culmination of a year-long collaboration. Conceived from the outset as a contribution to the Observatory's ongoing efforts, the first part of the thesis specifically takes the framework structure, previously developed by the team, as its methodological foundation and starting point. As a matter of fact, the aim has never been to propose an alternative theoretical model, but rather to enrich, refine, and operationally extend the existing framework already in use within institutional and corporate contexts. Accordingly, since the work is explicitly embedded within the Observatory's broader research agenda and intended to support its advancement and real-world applicability, no other academic frameworks or templates are here adopted.

As a strategic tool for analysing the multifaceted aspects of corporate sustainability, the adopted framework builds upon a generally accepted distinction of environmental, social, and governance dimensions, structured into multiple levels of categorization. This hierarchical shaping extends down to a third-level classification, allowing for a detailed exploration of each sustainability dimension, ensuring a precise alignment of KPIs with the specific aspects they measure.

4.2.1. Framework's Origins

Considering the topic's complexity and the interconnectedness of sustainability practices, the definition of this framework was a systematic process developed through seven distinct steps, leveraging on the collaboration of experts and researchers from various fields [219]. The first part of the work, which alone included six of the seven previously mentioned passages, consisted in the definition of impact areas through the selection and analysis of existing sustainability frameworks, such as ESG, SDGs, and the Doughnut model. During this phase, researchers identified, extracted, and synthesized common and unique themes across the already existing models, diving then deeper in the analysis by recognizing third-level potential subcategories

that could explore further commonalities and ensure a comprehensive coverage of topics.

Indicators related to the economic dimension, presented only in the SDGs framework, were at this point incorporated within the first-level categories of Environmental, Social, and Governance, as not namely related to sustainability but still characterized by a clear reference to at least one of its three major dimensions. Similarly, themes present only in one framework were included to ensure the consideration of a wide range of aspects, but all those that were too broad or not adequately detailed were removed to maintain focus and consistency.

The last step of the procedure, which represented a macro-passage by itself, consisted in synthetizing and grouping similar third-level categories under the unified labels, and in creating support entries to clarify and enhance the framework consultation. Specifically, this phase entailed the hierarchical grouping of the classified 69 themes across multiple levels, and the inclusion of 27 new ones to either bring together different voices or clarify what excessively generic.

The culmination of this process, which is constantly evolving as regulations are released, resulted in a robust framework that not only categorizes but also deeply analyses each aspect of corporate sustainability that companies should keep into account when drafting their reports. Indeed, basing on the collaborative efforts and expertise of various professionals, the developed model reflects a comprehensive understanding of sustainability that aligns with both current regulations and emerging trends, offering the possibility to companies to enhance transparency and accountability while simultaneously taking actionable steps towards more sustainable practices.

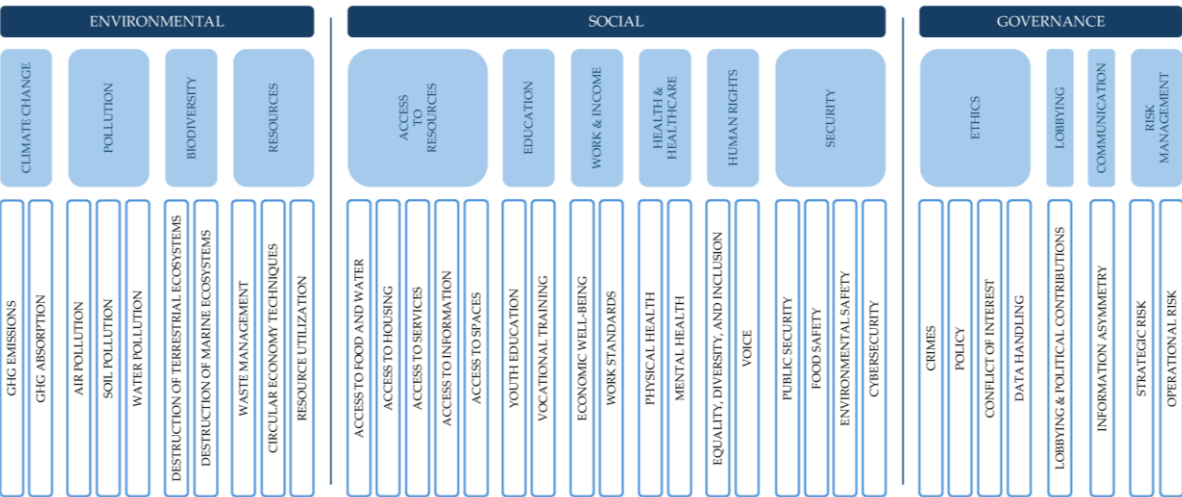


Figure 17: Observatory's ESG Framework

4.2.2. Dimensions and Categories

Environmental Sustainability

Environmental sustainability concerns all practices aimed at preserving, protecting, and improving the environment and ecosystems, leveraging on actions that maintain natural resources and avoid jeopardizing the ability of future generations to meet their needs. It is defined around the goal to create and retain conditions under which humans and nature can exist in productive harmony, managing resources in ways that ensure long-term ecological balance and conservation. Generally speaking, in the context of corporate behaviour, this dimension concerns all actions aimed at fighting climate change and pollution, preserving biodiversity, and responsibly using resources under a circular economy perspective. As a result, the second-level categories associated to this dimension are:

- **Climate Change**

Encompassing any alterations in the global atmosphere attributable to human activities, this category relates to phenomena such as global warming, glacier melting, sea-level rise, and shift in precipitation patterns, all due to the accumulation of greenhouse gases in the atmosphere.

- **GHG emissions:** release of GHGs in the atmosphere as a result of corporate activities related to manufacturing, energy production, and transportation, with the consequence that heat is trapped within the atmosphere and global temperature rises.
- **GHG absorption:** exploitation of natural carbon sinks, such as forests, oceans, and soil, and employment of Carbon Capture and Storage (CCS) techniques to absorb CO₂ and other hazardous gases from the atmosphere, contributing to global climate mitigation.

- **Pollution**

Concerning either soil, water, or air, pollution refers to the contamination of the natural environment by pollutants that disrupt the balance of ecosystems and cause harm to living organisms. Unlike climate change, it acts locally on a specific area, generating a direct impact on human health and on terrestrial and marine biodiversity.

- **Air pollution:** release into the air of substances generated from human activities and primarily categorizable into common and hazardous pollutants. These include particulates, ozone, and carbon monoxide, but also benzene, asbestos, and heavy metals in general, all of which can cause serious health effects on species.
- **Soil pollution:** contamination of soil by harmful chemicals or materials that alter its quality and composition, affecting its fertility and capacity to support plant and animal life. It can either depend on the release of

pesticides and radioactive substances or the excessive use of nitrogenous and phosphorous-potassium compounds.

- **Water pollution:** degeneration of rivers, lakes, and oceans' water quality because of their contamination with harmful substances, which often penetrate also in the near soils. Exactly as the previous case, it can be determined by the abuse of both chemicals and nutrients.

- **Biodiversity**

Ranging from plants and organisms to animals and their genes, biodiversity fundamentally represents the variety of life on Earth, extending beyond the physical forms and structures of organisms to include diversity in abundance, distribution, and interactions among system components. Manifesting itself in the three levels of genetic, species, and ecosystem, its fundamental role in providing essential services for living is constantly threatened by human activities such as deforestation, pollution, and climate change.

- **Destruction of terrestrial ecosystems:** degradation of land ecosystems through practices such as deforestation, agricultural expansion, chemical pollution, and introduction of invasive species, all of which can be partly mitigated by the implementation of conservation initiatives.
- **Destruction of marine ecosystems:** destruction of oceanic and coastal environments due to factors such as ocean acidification, nutrient pollution, and chemical contamination, which harm aquatic life and weaken marine structures.

- **Resources**

Combination of use, reuse, and disposal of resources, with the goal to minimize consumption and waste through the adoption of circular economy techniques that extend the lifecycle of materials from production to end-of-life, ensuring that anything not recyclable is disposed of responsibly.

- **Waste management:** responsible handling of waste that cannot be processed accordingly to circular economy principles, including urban, industrial, hazardous, and special materials.
- **Circular economy techniques:** strategies aimed at maintaining the value of products, materials, and resources within the economy for as long as possible, contrasting with the traditional linear “produce, use, dispose” model. To stretch the life of products as much as possible, different techniques can be chosen among reuse, regeneration, recycling, and reconversion.
- **Resource utilization:** responsible use of resources to minimize consumption and waste generation across various categories, including energy efficiency measures, water conservation, and reduction of all types of waste production.

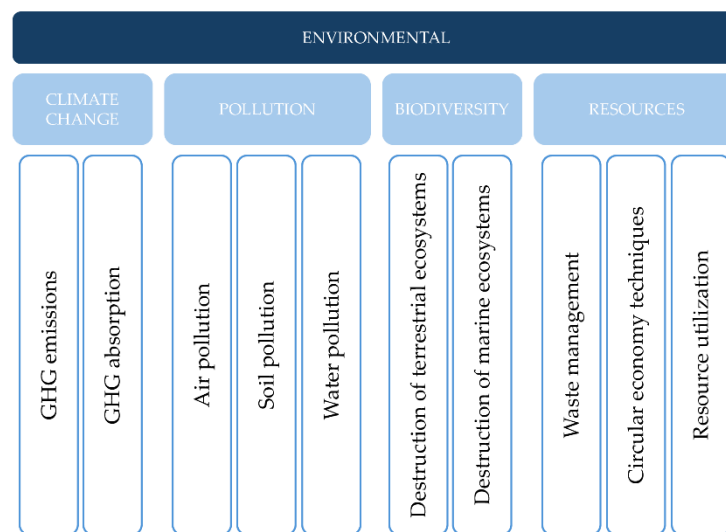


Figure 18: Environmental Sustainability Sub-Dimensions

Social Sustainability

Social sustainability refers to the ability of society to promote the well-being and cohesion of individuals and communities, ensuring that everyone enjoys equal economic opportunities and has access to necessary resources and educational services. It involves the goal of ensuring that all people live in adequate health conditions and in a way that allows them to fully exercise their rights. From a corporate perspective, it emphasizes the importance of managing human capital, such as labour rights, community health, education, and social justice, to ensure that social well-being improves alongside economic development. For this reason, the associated second-level categories are:

- **Access to resources**

Improvement and increase of access to essential resources, services, and spaces to ensure equality among populations.

- **Access to food and water:** capability to ensure that individuals and communities have access to nutritious food and potable water in sufficient quantities to meet fundamental needs and support good health, especially targeting populations in impoverished or disadvantaged conditions.
- **Access to housing:** opportunity for individuals and families to reside in safe and adequate housing, recognized as a fundamental human right and an essential component of human well-being.
- **Access to services:** availability, affordability, and timely setup of energy services, medical healthcare, transportation options, financial assistance, and legal support independently from individuals' social status.

- **Access to information:** provision of free and unconditional access to information for all citizens, promoting the democratization of knowledge across various domains, from scientific to general learning, and enhancing personal and professional development.
- **Access to spaces:** allocation of both private and public spaces for commercial activities, cultural and entertainment centres, and green areas, all of which able to foster community well-being and enhance life quality.
- **Education**

Acquisition of knowledge, skills, values, habits, and behaviours essential for people's development under both a personal and social point of view. As a fundamental human right and a central pillar for both individual and collective growth, this theme emphasizes the accessibility and quality of the learning experience.

 - **Youth education:** ease of access in terms of availability, cost, and quality, being crucial for providing the fundamental knowledge and skills needed for young individuals' development.
 - **Vocational training:** accessibility of professional training services that can help individuals advancing in career and meeting the evolving demands of the workforce, with a particular focus on their availability and cost-effectiveness.
- **Work and Income**

Focusing on economic well-being at both the individual and national levels, this category revolves around the working standards of employees and their well-being within the company and the surrounding environment.

 - **Economic well-being:** pursuit of achieving dignified levels of economic health for both individuals and national systems, especially focusing on those in poverty, with the goal to reduce social inequalities and fostering a more equitable society.
 - **Work standards:** set of criteria that focus on the specific needs and rights of workers, encompassing fair compensation, flexible working hours, workplace safety, abolition of child labour, and employee satisfaction through active involvement and job development opportunities.
- **Health and Healthcare**

Improvement of medical treatments and prevention for various issues, being them either physical, caused by human-related or natural factors, or mental, due to inborn conditions or difficult living standards.

 - **Physical health:** enhancement of healthcare and disease prevention, addressing both environmentally induced conditions such as respiratory diseases and cancers from air pollution, and those not linked to environmental factors.

- **Mental health:** improvement of medical services and prevention strategies for mental illness, including anxiety, stress-related disorders, and depression.
- **Human Rights**

Guarantee of equal civil, political, social, and cultural rights, both at the individual and national system levels, without any form of discrimination.

 - **Equality, diversity, and inclusion:** promotion of equality and inclusion by valuing diversity across dimensions such as gender, religion, ethnicity, disability, sexual orientation, age, and social status, to ensure fair treatment and opportunity for all individuals.
 - **Voice:** guarantee of freedom of expression and judgment, ensuring every individual's right to express ideas, opinions, and feelings without fear of repression or censorship. Together with it, the right to assemble and form groups and organizations for social, cultural, or political purposes.
- **Security**

Encompassing a broad range of protective measures and systems across physical, digital, environmental, and social domains, security consists in ensuring safety and stability of individuals, communities, and organizations through the adoption of proactive strategies.

 - **Public security:** protection of both individuals and the wider community from acts considered illegal by society and from dangers associated with mobility and transportation.
 - **Food safety:** management of food quality and safety standards to prevent adverse health effects related to contamination by chemical, physical, and biological hazards. It ensures that food products are not only safe but also nutritionally valuable, safeguarding public health against diet risks.
 - **Environmental safety:** prevention and mitigation of adverse natural events such as earthquakes, floods, hurricanes, and fires, reducing the impact of these threats and ensuring resilience in the face of their occurrence.
 - **Cybersecurity:** strategic protection of data to ensure its confidentiality, integrity, and availability. It involves safeguarding against unauthorized access and cyber threats while implementing robust measures that protect both personal and organizational information from breaches and attacks.

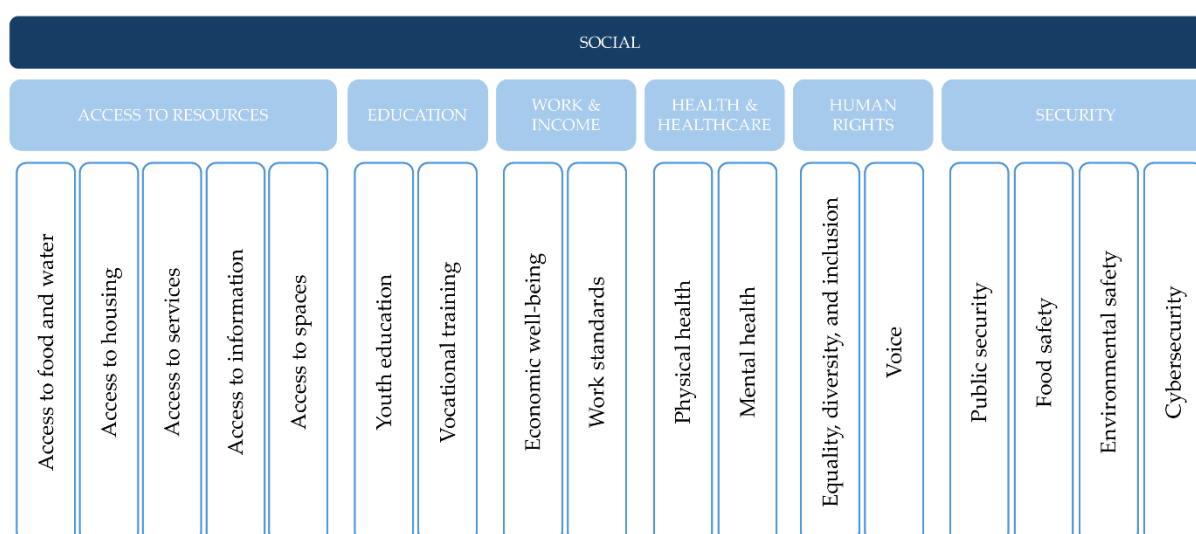


Figure 19: Social Sustainability Sub-Dimensions

Governance Sustainability

In the context of organizations, communities, or institutions' governance, sustainability refers to the adoption of frameworks, policies, and practices to ensure clear, accountable, and effective management. It aims to promote ethical decision-making and lobbying activities geared towards collective benefit, ensuring transparency in communication processes and the meticulous assessment of all risks associated with the entity's activities. In terms of behavioural evaluation, governance's second-level categories are:

- **Ethics**

Requiring adherence to high standards of integrity, transparency, and accountability, it represents the collection of moral principles and norms that guide the behaviour and decisions of individuals involved in managing organizations, governments, or entities.

- **Crimes:** illegal behaviours or actions that can compromise the integrity, transparency, and effectiveness of the governance system, ranging from corruption and fraud to abuse of power, laundering, and manipulation.
- **Policy:** set of guidelines, principles, and norms that not only outline the expected behaviour within an organization, but also contribute to ensure consistency and adherence to promoted strategic objectives and ethical values.
- **Conflict of interest:** situation where an individual or an organization possesses personal, professional, or financial interests that could potentially influence their ability to make impartial and objective choices, undermining the integrity of the decision-making process.

- **Data handling:** collection of practices, procedures, and regulations employed to manage, protect, and utilize personal and corporate data in accordance with laws, regulations, and ethical standards.
- **Lobbying and political contributions**

With the goal to promote the collective well-being of society rather than just serving the narrow interests of individual entities, this category includes all strategic activities of interest groups (lobbies) or companies aimed at influencing public policies and legislative decisions through persuasion.

 - **Lobbying and political contributions:** financial or in-kind donations made by individuals, corporations, unions, or other organizations to political parties in order to influence elections outcome and potentially impact policy decisions.
- **Communication**

Being crucial for building trust in stakeholders, communication is the ability of a specific entity to ensure transparency within every process, effectively sharing information, both internally and externally, in a manner that promotes openness and accountability.

 - **Information asymmetry:** condition for which there is an unequal distribution of relevant information among parties involved in a transaction or decision-making process. Addressing the issue means ensuring that all participants have a fuller understanding of the situation, which contributes to building trust and reducing the risk of opportunistic behaviours.
- **Risk management**

Officially defined as the process of identifying, categorizing, and evaluating threats that could impact the company's operations, risk management involves systematically addressing potential issues to minimize their likelihood and mitigate their effects, thereby ensuring organizational resilience and stability.

 - **Strategic risk:** factors that can negatively impact an organization at the corporate level, affecting its ability to achieve long-term objectives and threatening its market position.
 - **Operational risk:** management of issues related to the day-to-day operations of an organization, including processes, people, and systems, with the goal to reduce the likelihood of errors and ensure the smooth functioning of all operational aspects.

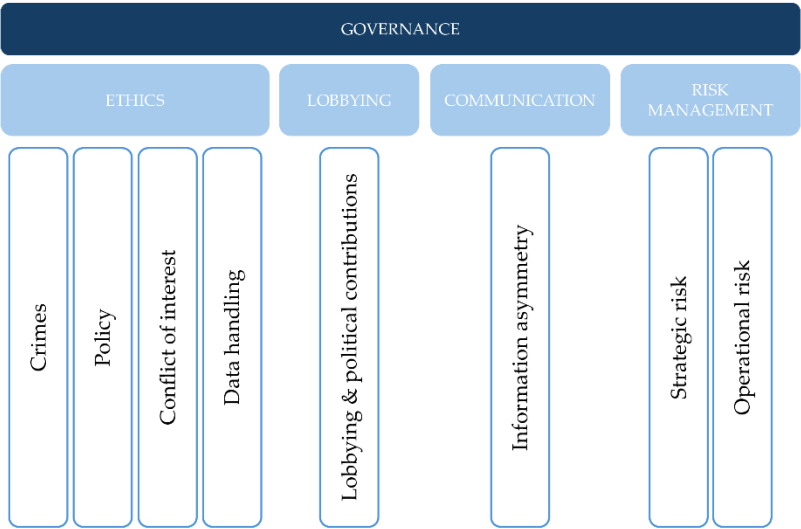


Figure 20: Governance Sustainability Sub-Dimensions

4.3. Framework Population

Following the definition of the framework’s structure and thematic dimensions, the subsequent phase of the research focused on its systematic population with a robust and representative set of Key Performance Indicators (KPIs). This process was conceived to ensure that each environmental, social, and governance sub-dimension would be supported by precise, measurable, and contextually relevant metrics, thus enabling comprehensive sustainability assessment and comparability across organizations. To achieve this, the work unfolded through a series of interlinked steps which collectively transformed the framework from a conceptual structure into a fully operational tool, ready to serve both analytical and practical purposes in corporate sustainability evaluation.

4.3.1. KPIs Collection

After concluding the previously outlined literature review, which meticulously mapped out the landscape of sustainability reporting within corporate practices, the focus of the research shifted towards an in-depth exploration and classification of the most commonly used metrics and KPIs. For this reason, the same 84 papers that were formerly read to give information about the broader context of sustainability assessment and digitalization purposefulness were now analysed again to identify those that originally included well-defined and specific metrics. Out of the total, around 30 articles were recognized as instrumental, mainly corresponding to the ones

that in the previous categorization had the purpose to define a new set of KPIs or single assessment index.

4.3.2. KPIs Categorization

Once the relevant papers were identified and the KPIs within them noted, the next step involved the systematic collection and organization of the latter into a specifically designed Excel file, which served as a critical tool for managing the data and facilitating their subsequent analysis. Right from the start, each KPI was meticulously recorded in the spreadsheet with a clear reference to its originating paper, and thoughtfully assigned to one of the three fundamental dimensions of environmental, social, or governance sustainability. This categorization was conducted with the intention to cover all essential scopes, independently from how papers' authors originally intended to divide indicators in the various classes. As a matter of fact, while the term ESG has become of great importance in recent years, and no company today can afford to overlook its significance, the governance related aspects have often been overshadowed or inadequately integrated. Indeed, among the selected ones, and how formerly highlighted, many studies have tended to merge governance indicators with economic or social ones, creating less defined and more general categories while also diluting the distinct and critical nature of governance in sustainability practices.

By distinctly highlighting and properly categorizing indicators, this first step of the overall methodology aimed to rectify previous misclassifications and to ensure a balanced and thorough assessment of all three sustainability dimensions. Moreover, while selecting KPIs from the chosen texts, no emphasis has been given to economic indicators, which were often included but traditionally focus on financial performance rather than sustainability impacts, being certainly important for overall business analysis but not strictly related to environmental, social, or governance performance. As a result, any economic indicators encountered during the review were carefully evaluated and, unless clearly providing relevance to sustainability practices, excluded from the dataset.

4.3.3. KPIs Allocation

Starting from the previously conducted broader classification, which allowed to ascribe each indicator to one of the three sustainability dimensions, a further step was taken to delve deeper into detail and represent all nuances of sustainability impacts.

The process of assigning each KPI to the most appropriate subcategory involved a thorough analysis of the context in which each indicator was used, as well as the consultation of the definitions eventually provided in some of the analysed academic

papers. This assignment was not merely a mechanical sorting of data but a thoughtful consideration of where each KPI would provide the most meaningful insight into sustainability practices. Obviously, being the described framework an original work, initial documents did not provide any indication of how to divide proposed KPIs into such specific categories, and the author had to rely on their own analytical skills and understanding of sustainability practices to make these determinations. Overall, each decision regarding the placement of a KPI was made with an aim to enhance the framework's applicability and effectiveness in measuring and interpreting complex sustainability data.

In general, the goal was to attribute each KPI to one specific third-level category, but the process revealed such a pervasive nature of some indicators that they could be allocated to more than one subgroup. For instance, the amount of Hazardous Waste produced was easily associable to both waste management practices and soil pollution, making it illogical to confine its impact to a single area when it clearly influences both. Indeed, this and few other dual placements highlight the interconnected nature of sustainability issues, where a single KPI can illuminate multiple aspects of a company's environmental impact.

4.3.4. Integration of Additional Sources

European Directives

Following the categorization of KPIs derived from academic sources, the following step involved the integration of indicators outlined in European directives and, in particular, in the document *"KPIs for ESG - A Guideline for the Integration of ESG into Financial Analysis and Corporate Valuation"* (2010) and the *"Implementation Guidance 3 - List of ESRS Data Points"* published by the European Financial Reporting Advisory Group (EFRAG) in May 2024. This passage was completed to align academic findings with the established regulatory standards and to ensure that the successively developed framework could be both reflective of scholarly insights and compliant with current legal sustainability practices within the EU. Obviously, as it was expected that many of the already classified KPIs coincided with the ones specified in authoritative documents, being the latter a fundament for corporate reporting, a careful comparison was conducted to ensure thoroughness and avoid redundancy. As a result, only those indicators that offered new insights or filled existing gaps in the academic collection were selected for integration into the model, and always highlighted in a different colour to mark the distinction between descriptive practices and normative.

In general, this step was essential to fortify the framework's robustness and relevance, enhancing it with legally vetted and authoritative indicators that are essential for

compliance and reporting but could not be found in normal practices and current literature.

Companies' Reports

Next to the integration of KPIs from academic literature and European directives, the final step in populating the sustainability framework involved incorporating indicators sourced from organizations and institutions globally recognized for their exemplary practices and methodological rigor. To strengthen the practical dimension of the model and ensure coverage of underrepresented areas, particularly within the social and governance pillars, this phase focused on three strategically selected sectors: fashion, food, and ICT.

The choice of these areas was not arbitrary but rooted in both economic relevance and sustainability complexity. In the national context, in fact, retail companies represent the largest group of enterprises, with over 1.44 million active firms in Italy as of 2022 [155], and it is their dominant presence within the economic structure to position them at the forefront of market dynamics and sustainability transitions. In particular, food and fashion have been identified as emblematic industries due to their significant environmental impact, supply chain complexity, and high consumer visibility. According to ISTAT's Retail Trade Report [156], food products account for 41.2% of monthly national retail sales, while clothing represents the leading non-food segment at 10.0% out of the remaining expenditure. Further supporting this argument, the market report published by Global Data in June 2022 [157], states that Food & Grocery is the dominating sector with EUR 203.1 bn, while Clothing & Footwear is the fastest growing one. Last but not least, it must be considered that these industries are emblematic of the Made in Italy brand, which is synonymous worldwide with high quality, craftsmanship, and innovation, making them particularly representative of national economic and cultural influence globally.

The inclusion of the ICT sector complements this selection by addressing the digital and technological dimensions of sustainability, which occupy an always more fundamental spot in today's fast-changing environment. ICT is the most heavily invested sector globally, with Forrester forecasting over 5.6 trillion USD in global spending (more than 17% of world GDP) [158] and Eurostat reporting its contribution to the EU's total gross value added at 5.5%, with consistently strong growth [159]. This sector is not only economically powerful but also functionally essential, as it serves as an enabler of sustainable transformation across industries. Its challenges, such as energy consumption, data governance, and system resilience, demand in fact robust ESG strategies, making it an ideal reference point for assessing digital sustainability.

Once these sectors were selected, representative organizations and sources were identified to extract high-quality KPIs grounded in real-world application and

methodological precision. Within fashion, Patagonia was chosen for its internationally acclaimed sustainability model, as the company is a pioneer in ethical sourcing, environmental activism, and circular economy practices, and is widely cited in both academic and practitioner circles for its transparency and commitment. Among its most notable initiatives is the donation of 1% of all sales to environmental causes, as well as its public traceability of supply chains.

In the food sector, Nestlé was selected due to its comprehensive sustainability strategy and global scale. As one of the world's largest food and beverage companies, Nestlé has consistently demonstrated a deep commitment to environmental protection, responsible sourcing, community development, and human rights in its operations. Its sustainability reporting reflects not only a high level of detail but also a proactive alignment with international standards and long-term ESG goals.

Finally, for the ICT sector, indicators were extracted from the National Institute of Standards and Technology's (NIST) Technical Series Publications. The foundation was selected for its scientific credibility, methodological robustness, and its role as a leading authority in defining standardized performance measures for complex systems. Its works provide structured, evidence-based sustainability indicators in areas such as data governance, cybersecurity, digital infrastructure resilience, and energy efficiency, dimensions that are critical but often absent in corporate ESG reporting.

Together, these sources allowed the framework to be populated with a series of new, practical KPIs that addressed previously identified gaps, particularly in the social and governance domains. Examples include indicators related to employee healthcare access, equitable bonus distribution, community engagement initiatives, and collective bargaining rights, as well as digital risk management, data transparency, and ethical use of AI systems. Distinctly highlighted to maintain clarity and distinguish between academically derived and practically applied measures, these real-world indicators ensured to fill existing gaps and to provide additional dimensions of sustainability assessment relevant to their respective industries.

4.3.5. Creation of Subcategories and Elimination of Duplicates

At this point, after the first framework's population, each third-level category was scrutinized for potential overlaps and redundancies, as well as for identifying some central themes around which similar KPIs revolved.

Focusing the attention on a single column at time, indicators that were listed separately but represented very similar sustainability issues were merged together to streamline the dataset and ensure each unique aspect could be represented without unnecessary repetitions. The result was not only a simplification of the framework but also a

strengthening of its analytical power by consolidating closely related indicators into single, more impactful metrics.

In parallel with the elimination of duplicates, the review of all KPIs listed within the same third-level category revealed recurring themes that suggested the introduction of fourth level classes. It was not rare, in fact, especially for the most popular and acknowledged impact categories, to find extremely long lists that resulted in cumbersome navigation and potential confusion, asking for a refinement of the framework's structure and the implementation of a more user-friendly outline. For example, within a broad category like "Resource Utilization", which by herself encompasses several aspects and nuances, the clustering of indicators in subtitles such as "Water", "Energy", "Electricity", "Materials" and "Others" effectively segmented a vast array of information into more digestible parts.

The identification of these common threads not only allowed to capture the essence of each group of indicators, but also enhanced the framework's organization facilitating a more structured and intuitive navigation. Indeed, this finer subdivision contributes to ensure that each KPI is not only precisely categorized but also easily accessible, supporting a more effective analysis and a valuable application of the framework in sustainability assessment. Moreover, this detailed categorization allows companies to clearly identify areas of strength and weakness within their operations, providing them with the insights necessary to target interventions more specifically. This precision enables stakeholders to pinpoint specific areas for improvement and monitoring within broader contexts, thus optimizing sustainability performance and strategic decision-making.

4.3.6. Attribution of Metrics

Having the goal to create an objective and comprehensive framework that could be used by companies to monitor their sustainability performance, the specification of formulas for each of the identified indicators emerged as a fundamental step in the methodology. Indeed, the effectiveness of any assessment model largely hinges on its ability to provide measurable and verifiable data, and the definition of KPIs themselves largely relies on the provision of clear metrics to be used for evaluating progresses, driving strategies, and helping organizations benchmark. Fundamentally, without specific and consistent formulas, the ability to quantify corporate sustainability performance accurately and comparably across different contexts would be significantly compromised.

A major challenge for this step was represented by the fact that a substantial portion of the KPIs extracted from the academic papers did not have explicitly defined formulas, but only approximative definitions or nothing at all. The majority of authors,

in fact, focused on highlighting the most commonly used indicators by companies or those recognized by general standards, providing an extensive list of options but no specific metric for their calculation. Especially in the case of surveys, results often coincided with the collection of generally accepted KPIs that, although representative of common industry practices and agreement on targets in various domains, often lacked the association of detailed computational methods. In these cases, in fact, the goal was more to evaluate the prevalence of indicators' usage than to explicitly define them, and the main output consisted in a ranking based either on the frequency of their adoption or the recognition by respondents of their usefulness in corporate practices. In a similar way, most of the documents categorized as Literature Reviews limited themselves to acknowledge the variety that exists in sustainability assessment methods and to identify the most widely proposed indicators within the academic landscape, eventually matching them with the 17 SDGs proposed by the United Nations (ex. [56]). Again, also when the goal was to create analytical models based on available indicators, the focus was more on highlighting and justifying their weight than to clearly provide formulas, consequently leaving space for interpretation and guessing (ex. [40]).

Fortunately, some papers were highly detailed in defining indicators, providing comprehensive information on their formulas, units of measure, and even the specific categories and subcategories to which they belonged (ex. [88]), being therefore extremely helpful for the research. Complemented by the author's knowledge and supplemented with additional information sourced from the internet, these well-documented articles facilitated the precise matching of each KPI with an appropriate formula, thereby contributing to the creation of a robust and analytical framework.

The metrics associated with different indicators varied significantly, particularly in relation to the dimensions they addressed and the nuances of their definitions. For example, while environmental indicators often involved scientific computations, such as sums and ratios of clearly definable quantities, social and governance indicators were more frequently linked to rating systems, such as Likert scales, and typically evaluated through the distribution of surveys among employees and/or stakeholders. However, even within the social and governance dimensions, efforts were made to minimize reliance on overly generic and subjective metrics and, whenever feasible, the author prioritized the development of ratios and quantifiable formulas that would enhance the comparability of companies worldwide. The guiding principle of the whole process was in fact to establish a more objective and measurable framework, ensuring that assessments could be consistently applied across different contexts and regions, thus providing a more standardized and rigorous basis for evaluating corporate sustainability practices.

At the end, as a consequence of everything said in advance, the obtained units of measure vary significantly, ranging from absolute values typically bounded between

0 and 1, to quantities computed through sums and differences, and judgments derived from qualitative scales. This diverse nature overall highlights the simultaneous presence of both quantitative and qualitative metrics within the same framework, which in this way answers to the need emerged from the academic review to leverage on a combination of both measures to obtain a broader and more complete image. As highlighted by one of the interviewed of [44], in fact, data is useful but often can't tell the whole story, making it necessary to introduce some more subjective measures that can help picturing what too nuanced to be expressed in numbers.

4.3.7. Gaps Filling

The population of the framework, followed by the specification of distinct metrics for each KPI, made it evident that certain third-level categories previously defined presented with sparse or no data, revealing gaps that could undermine the comprehensiveness of the analysis. Since the framework had been appositely elaborated by the D&S Observatory to be as completed as possible, covering all facets of corporate sustainability, it became evident the necessity to integrate the obtained results with additional metrics that could offer deeper insights and fill any existing gaps. This integration aimed to enhance the framework's ability to provide a detailed and nuanced understanding of each sustainability dimension, ensuring no critical area was overlooked.

To address the deficiencies recognized in some categories, a proactive approach consisting in extensive online research and independent creation was adopted. The task began by searching on the internet some additional information that could have been omitted in the analysed documents, both qualitative and quantitative, coming from either regulations, articles, studies, and research. The goal was to understand how to measure those aspects of sustainability that were underrepresented in the initial findings but, being the topic of sustainability assessment slightly controversial and not particularly developed, little information was actually found. As a result, it became almost necessary to undertake the creative development of new KPIs that based on a deep understanding of the specific needs of underpopulated categories and on the definition of metrics that could align with the objectives of the framework while maintaining integrity and balance.

Clearly distinguishing them from the ones obtained through academic review and standards analysis, a new set of indicators was developed to ensure that each sub-dimension could include at least a few metrics, and that the fundamental idea behind each of them could be adequately represented. Particularly valuable was not only the careful reading of the D&S Observatory's framework definition [218], but also the direct engagement with the responsible team to both validate the correctness of the developed indicators and gather insights for the definition of new ones. While

facilitating a deeper understanding of each category's unique aspects, the collaborative discussion contributed to identify those scopes that might have been initially overlooked but whose integration could give a broader and more comprehensive perspective of the current global sustainability landscape.

While third-level categories under the broader environmental sustainability dimension were in great part highly populated, with the only exceptions of GHG absorption and preservation of both terrestrial and marine biodiversity, an intense work had to be done to fill in the ones associated with the social and governance perspectives.

In relation to the first one, having the goal to develop a framework that could be easily adopted by companies to assess the impact of their own performances, a strong focus was put on the living and working conditions of internal employees. Indeed, while categories such as access to resources and security could be eventually extended to a country population as a whole, it was decided to give a stronger emphasis to the benefits offered by a company to its own workers, including opportunities for growth and healthcare. Several indicators were therefore developed with the only objective to understand how organizations take care of their employees during daily operations, providing them funds, premiums, and mental support, but also making them available open spaces for recreation, canteens for nutritious food, and information sessions for personal development. Fundamentally, since not all companies carry on projects that have repercussions on the surrounding communities, and since an entity's success highly depends on the atmosphere that can be respired inside its facilities, it appeared essential to emphasize metrics that reflect the internal culture and employee well-being directly within the company. By concentrating on these internal aspects, in fact, the framework aims to provide organizations with actionable insights that promote not just compliance with external standards but also foster an environment that supports sustainable growth and a positive workplace culture.

On the other side, in regard to the governance dimension, attention was majorly reserved to those categories that were poorly addressed by academic literature and official standards due to their complex nature and the challenges in defining and measuring them. Spanning from the correct handling of employees and customers data to the appropriate disclosure of lobbying activities and political contributions, a great emphasis was given to introducing fourth-level categories that were still missing but needed to be properly managed. Efforts were made to assess the reduction of information asymmetry through comprehensive reporting and certified transparency, and indicators were developed to measure the effectiveness in managing human and machine errors by adopting sustainable production practices and implementing robust monitoring systems. The overall goal was to enhance a company's accountability and to ensure the establishment of ethical governance practices that

align with both regulatory requirements and social standards, thereby strengthening the overall integrity and transparency of corporate operations.

In the extremely complex scenario of corporate sustainability assessment, the population of the D&S Observatory's framework and the collaborative discussion with the team were fundamentally designed to address the significant gaps observed between existing corporate practices and the achievement of Sustainable Development Goals (SDGs). Upon thorough analysis, these shortcomings are predominantly due to an absence of the requisite skills, tools, or guidance needed for effective measurement, further exacerbated by most companies' insufficient recognition of the full scope of their activities and the subsequent impacts. This initiative is therefore aimed at not only enhancing corporate awareness regarding sustainability but also at providing clear, practical metrics that can empower organizations to comprehensively evaluate their practices and align them with SDG commitments.

4.4. Framework Final Outline

To conclude the presentation of the developed framework, the following section provides its visual representation, offering a synthetic yet comprehensive view of the structure, dimensions, and corresponding Key Performance Indicators. Given the extensive number of categories and indicators included, for each ESG category the visualization is organized to display one second-level dimension at a time, so to enhance clarity and ensure that details remain legible while also allowing each area to be fully appreciated without overwhelming the reader. Additionally, before the presentation of each dimension, a brief narrative and a complementary illustration introduce the selected KPIs, clarifying not only their role and contextual relevance but also their function within the framework. Indeed, by highlighting their interconnections and explaining the rationale behind their placement in a given area, this step ensures that the visualization is accompanied by a clear interpretative guide, helping the reader to understand both the logic of the classification and the broader significance of each indicator.

Framework Legend

A dedicated colour legend supports the interpretation of each diagram, signalling at a glance the provenance of the indicators:

- White: extracted from peer-reviewed academic literature
- Light orange: derived from European Union directives [101]
- Yellow: specified in the European Sustainability Reporting Standards (ESRS) [102]

- Green: developed in collaboration with the Observatory Digital & Sustainable team
- Purple: taken from Nestlé annual report [220]
- Light blue: taken from Patagonia annual report [221]
- Gray: taken from publications by the National Institute of Standards and Technology (NIST) [194]

Beyond its aesthetic function, this chromatic mapping highlights the multidimensional foundation of the framework, revealing how regulatory standards, scholarly research, corporate best practices, and original contributions intertwine to form a unified, actionable tool for sustainability assessment.

4.4.1. Environmental Dimension

Climate Change

Within the **GHG Emissions** column, the first cluster of indicators under *Overall Emissions* cluster provides an aggregate view of the company's carbon footprint. *Total GHG Emissions in CO₂ Equivalents* and *Tons of CO₂ Emissions* represent the most direct and internationally comparable measures, while *Emissions Intensity* links emissions to output, thus capturing efficiency improvements over time. The inclusion of *Total Tons of HFCs and PFCs* adds an important nuance, since these gases, though less discussed, have a much higher warming potential and therefore significantly alter the overall climate impact. Moving to *Emissions by Scope*, the indicators break down emissions into *Scope 1*, *Scope 2*, and *Scope 3*, alongside *Tons of Stationary Combustion*, aligning with standard reporting requirements and allowing companies to distinguish between direct emissions, energy-related indirect ones, and those linked to the value chain. The articulation of these categories not only facilitates compliance but also highlights where reduction efforts should be prioritized, given that Scope 3 often represents the majority of total emissions. The third cluster, *Emissions Reduction*, shifts the focus from measurement to performance over time, with indicators such as *Emissions Payback Time* that offer a dynamic perspective on how quickly mitigation initiatives offset their initial implementation costs in terms of carbon. *CO₂ Emissions Reduction* and *Achieved GHG Emissions Reduction* provide clear before-after comparisons with respect to established baselines, while indicators such as *Provision of Greenpower* underline the role of renewable sourcing in supporting long-term decarbonization, and *Scope 4 Emissions* encourages companies to account for avoided emissions through products or services that reduce impacts in downstream use.

On the other side of the framework, the **GHG Absorption** column captures the set of practices that balance emissions with compensatory actions. Under *Use of Materials*, *Emissions Mitigants* and *Low Emitting Materials Used* emphasize design and

procurement strategies that lower emissions at source, demonstrating the link between material choices and environmental outcomes. *Investments and Purchases* then extends the focus to financial and organizational commitment, with *Investment in Decontamination Actions* and *Total Carbon Credits Purchased* reflecting the willingness to dedicate resources to remediation or market-based compensation. Finally, the *Efficiency* cluster addresses the technological and operational dimension of absorption, with *Carbon Capture Efficiency* and *Number of Implemented Technologies* measuring the effectiveness and scope of innovative solutions, and *Total GHG Removals and Storage* translating these initiatives into tangible results. Complementary metrics such as *Total Carbon Credits Usage*, *Remaining Carbon Credits*, and *Carbon Credits Use Rate* ensure transparency and accountability, clarifying to what extent offsetting instruments are used responsibly and how they interact with real emissions reductions.

Altogether, this combination of emission- and absorption-related KPIs creates a balanced system where it is possible not only to quantify the climate impact of corporate operations but also to track the strategies adopted to mitigate, compensate, and ultimately align business activities with global decarbonization pathways.

Climate Change			
GHG Emissions		GHG Absorption	
Overall Emissions		Use of Materials	
Total GHG Emissions in CO2 Equivalents	$\sum GHGi \times GWPi$	Emissions Mitigants	$\sum Emission\ Saved$
Tons of CO2 emissions	$\sum CO2$	Low Emissioning Materials Used	$\frac{Volume\ of\ Low\ Emitting\ Materials}{Total\ Materials\ Volume} \times 100\%$
Emissions Intensity	$\frac{\sum GHGi}{Output}$	Investments and Purchases	
Total Tons of HFCs and PFCs	$\sum (HFCs + PFCs)$	Investment in Decontamination Actions	score [Yes, No]
Emissions By Scope		Total Carbon Credits Purchased	$\sum Carbon\ Credits\ Purchased$
Tons of GHG Emissions - Scope 1	$\sum GHGi \times GWPi$	Efficiency	
Tons of GHG Emissions - Scope 2	$\sum GHGi \times GWPi$	Carbon Capture Efficiency	$\frac{Volume\ of\ CO2\ Captured}{Total\ CO2\ Emissions} \times 100\%$
Tons of GHG Emissions - Scope 3	$\sum GHGi \times GWPi$	Number of Implemented Technologies	Number
Tons of Stationary Combustion	$\sum GHGi \times GWPi$	Total GHG Removals and Storage	$\sum GHG$
Emissions Reduction		Total Carbon Credits Usage	$\sum Carbon\ Credits\ Used$
Emissions Payback Time	$\frac{CO2\ Emitted\ for\ Implementation}{Annual\ CO2\ Emission\ Reduction}$	Total Remaining Carbon Credits	$\sum CC\ Available - CC\ Used$
CO2 Emissions Reduction	$CO2\ baseline - CO2\ current$	Carbon Credits Use Rate	$\frac{CC\ Usage}{Total\ CC\ Available} \times 100\%$
Provision of Greenpower	$\frac{Greenpower\ Procured}{Total\ Energy\ Procured}$		
Acheved GHG Emissions Reduction	$GHG\ baseline - GHG\ current$		
Tons of GHG Emissions - Scope 4	$\sum GHG\ standard\ product - GHG\ new\ product$		

Table 5: Environmental Dimension Framework - Climate Change

Pollution

The **Air Pollution** indicators begin with a general overview of atmospheric releases through measures such as *Air Emissions* and *Total SC Air Emissions*, complemented by *Air Pollution Prevention Level* which evaluates the extent to which pollutants are captured or eliminated before being released. This dual perspective, on both emitted quantities and mitigation capacity, offers a balanced understanding of performance. More granular indicators under *Specific Pollutants*, including CO, SO₂, NO_x, and *Particulate Matter (SPM)*, allow companies to trace the impact of their most harmful emissions individually, while additional metrics on heavy compounds such as *Lead* or *Fluorine* capture risks linked to persistent and toxic substances. The presence of *Human Toxicity* as an impact-oriented KPI further strengthens the link between pollutant release and direct consequences on health, shifting the focus from pure volumes to their societal significance.

Soil Pollution KPIs emphasize contamination sources, with *Hazardous Waste*, *Waste to Landfill*, and *Radioactive Emissions* reflecting the main vectors through which soil quality is compromised. While aggregated measures such as *Emissions to Soil by Pollutants* help quantify the scale of the problem, impact-oriented indicators like *Acidification Potential* and *Terrestrial Toxicity Potential* go further by translating emissions into their ecological consequences. This layered structure allows not only for accountability in waste handling but also for an assessment of how emissions compromise soil ecosystems over the long term.

In the case of **Water Pollution**, the framework mirrors a similar logic but adapts it to aquatic ecosystems, with indicators on *Heavy Metals*, *VOCs*, or *Radioactive Emissions* highlighting the most hazardous contamination sources and *Emissions to Water by Pollutants* providing a consolidated measure. The KPI *Percentage of Emissions Occurring in Areas at Water Risk* introduces a crucial contextual dimension, recognizing that the same emission may have more severe implications when occurring in vulnerable basins. Impact indicators such as *Eutrophication* and *Human Toxicity* then translate these data into ecological and health outcomes, while the inclusion of *Metric Tons of Discarded Fishing Nets Removed from the Ocean*, an initiative-based KPI taken from Patagonia's annual report, signals the importance of proactive restorative actions alongside traditional pollution monitoring.

Overall, the Pollution dimension is structured to move from a general quantification of emissions to a pollutant-specific detailing, and finally to impact assessment and mitigation initiatives. This progression not only ensures comparability across companies but also encourages organizations to look beyond simple compliance and to understand how emissions interact with ecosystems and human health.

Pollution					
Air Pollution		Soil Pollution		Water Pollution	
General Air Emissions		Contamination Sources		Contamination Sources	
Air Emissions	$\sum \text{Specific Pollutants}$	Hazardous Waste	$\sum \text{Mass Hazardous Materials}$	Heavy Metal	$\sum \text{Heavy Metals}$
Total SC Air Emissions	$\sum \text{Air Emissions} \times \text{Scope } 1,2,3$	Waste to Landfill	$\frac{\text{Waste Sent to Landfill}}{\text{Total Waste Generated}} \times 100\%$	NaOH Emissions	$\sum \text{NaOH}$
Air Pollution Prevention Level	$\frac{\text{Pollutants Capt/Elim}}{\text{Total Potential Pollutants}} \times 100\%$	Radioactive Emissions	$\sum \text{Mass Radioactive Materials}$	VOCs Emissions	$\sum \text{VOCs}$
Specific Pollutants		Emissions to Soil by Pollutants	$\sum \text{Emissions}$	Radioactive Emissions	$\sum \text{Radioactive Materials}$
CO Emissions	$\sum \text{CO Emissions}$	Impact		Emissions to Water by Pollutants	$\sum \text{Emissions}$
SO2 Emissions	$\sum \text{SO2 Emissions}$	Acidification Potential	$\sum (Mi \times \text{SO2 eq})$	Percentage of Emissions Occurring In Areas at Water Risk	$\frac{\text{GHG Emissions in Water Risk Areas}}{\text{Total Emissions}} \times 100\%$
NOx Emissions	$\sum \text{NOx Emissions}$	Terrestrial Toxicity Potential	$\sum (Mi \times \text{CTUh})$	Impact	
SOx Emissions	$\sum \text{SOx Emissions}$			Eutrophication	$\sum (Mi \times \text{Neq})$
SPM Emissions	$\sum \text{SPM Emissions}$			Human Toxicity	$\sum (Mi \times \text{CTUh})$
NMVOC Emissions	$\sum \text{NMVOC Emissions}$			Initiatives	
Dust Emissions	$\sum \text{Dust Emissions}$			Metric Tons of Discarded Fishing Nets Removed from the Ocean	Total Mass
Lead Compounds Emissions	$\sum \text{Lead Compounds Emissions}$				
Fluorine Compounds Emissions	$\sum \text{Fluorine Emissions}$				
Aldehydes Emissions	$\sum \text{Aldehydes Emissions}$				
Impact					
Human Toxicity	$\sum \text{Gas} \times \text{CTUh}$				

Table 6: Environmental Dimension Framework – Pollution

Biodiversity

The **Protection of Terrestrial Ecosystems** dimension is articulated around three complementary clusters. Under *Habitat Conservation*, indicators such as *Level of Protection or Restoration of Habitat* and *Spill to Destination* capture direct efforts in preserving or restoring natural environments, while more systemic metrics like *Purchases from Suppliers Adopting Regenerative Practices* reflect the importance of extending conservation principles along the supply chain. Certification-based KPIs, including *Number of Active Biodiversity Certifications* and *Percentage of Certified Operations*, then provide assurance mechanisms that strengthen credibility and comparability, signalling a commitment that is not only voluntary but externally verified. The second cluster, *Planning and Design*, emphasizes how land is selected, occupied, and managed in relation to biodiversity-sensitive areas. Metrics such as *Level of Effective Site Selection*, *Land Occupation*, and *Soil Use Rate* show whether expansion is conducted responsibly, while the indicators on *Sites Near Protected Areas* and *Nature-Oriented Area On Site* underline the spatial interaction between business operations and ecosystems, overall highlighting how companies can anticipate impacts at the design stage, rather than simply mitigating them ex post. The third cluster ultimately addresses *Destruction of Ecosystems*, focusing on pressures that undermine terrestrial biodiversity. *Deforestation* is measured both in absolute terms and through the *Adoption of Policies to Address Deforestation*, which ensures that quantitative reductions are supported by strategic governance, while *Total Use of Land Area* finally adds a broader perspective and signals the extent of human footprint on ecosystems.

On the **Protection of Marine Ecosystems** side, *Water Conservation* offers a parallel logic, with indicators like *Destination of the Spill* and *Number of Marine Conservation Programs Supported* capturing both risk management and proactive engagement. The adoption of *Sustainable Oceans or Seas Practices*, supported again by biodiversity certifications and certified operations, mirrors the terrestrial approach and ensures alignment across ecosystems. Finally, the KPI *Metric Tons of Discarded Fishing Nets Removed from the Ocean* represents a concrete initiative with strong communicative value, as it directly links business practices to visible restoration of marine habitats. The section closes with *Planning and Design* applied to water contexts, where *Provision of Water Efficient Landscaping* demonstrates how even site-level interventions can contribute to resource conservation.

Overall, the Biodiversity indicators move from direct habitat protection to supply chain and design considerations, complemented by restorative actions. This layered approach ensures that corporate responsibility towards biodiversity is not restricted to compliance but integrated into operational, strategic, and even cultural dimensions of sustainability.

Biodiversity			
Protection of Terrestrial Ecosystems		Protection of Marine Ecosystems	
Habitat Conservation		Water Conservation	
Level of Protection or Restoration of Habitat	$\frac{\text{Area Protected}}{\text{Total Targeted Area}}$	Destination of The Spill	$\frac{\text{Volume Contained} - \text{Volume Released}}{\text{Volume Released}}$
Spill to Destination	$\frac{\text{Volume Contained} - \text{Volume Released}}{\text{Volume Released}}$	Number of Marine Conservation Programs Supported	Number
Purchases from Suppliers Adopting Regenerative Practices	$\frac{\text{Regenerative Purchases}}{\text{Total Purchases}}$	Adoption of Sustainable Oceans or Seas Practices	score [Yes, No]
Number of Active Biodiversity Certifications	Number	Number of Active Biodiversity Certifications	Number
Percentage of Certified Operations	$\frac{\text{Certified Operations}}{\text{Total Operations}} \times 100\%$	Percentage of Certified Operations	$\frac{\text{Certified Operations}}{\text{Total Operations}} \times 100\%$
Planning and Design		Metric Tons of Discarded Fishing Nets Removed from the Ocean	Total Mass
Level of Effective Site Selection	$\frac{\text{Sites Meeting Criteria}}{\text{Total Number of Sites}}$	Planning and Design	
Land Occupation	Hectares	Provision of Water Efficient Landscaping	$\frac{\text{Saved Water}}{\text{Water Used for Landscaping}}$
Soil Use Rate	$\frac{\text{Soil Used for Production}}{\text{Available Soil Area}}$		
Number of Sites Near Protected Areas	Number		
Areas of Sites Near Protected Areas	Total Area		
Nature-Oriented Area On Site	Total Area		
Destruction of Ecosystems			
Deforestation	Hectares		
Adoption of Policies to Address Deforestation	Score [Yes, No]		
Total Use of Land Area	Total Area		

Table 7: Environmental Dimension Framework – Biodiversity

Resources

The **Waste Management** indicators span the entire chain from generation to recovery. *Total Waste Generated*, *Industrial Wastewater Generation*, and the *Waste Generated per Unit Produced* give a quantitative picture, while the *Percentage of Hazardous Waste*, *E-Waste*, and the *Quality of Effluents Generated* ensure that impacts are assessed not only by volume but also by risk. The second cluster shifts to organizational capacity, with the *Provision of a Waste Management Plan*, the use of *Wastewater Technologies*, and practices such as *Waste Mitigants (Diverted from Disposal)* or *Waste Generated that is Energy-Valued*, showing how companies seek to reduce or valorise waste. Finally, *Waste Disposal and Recovery* introduces accountability for end-of-life, where the *Disposal Rate of Dangerous Waste*, the *Total Waste Recovered*, and the *Waste Transferred to Third Parties* clarify whether upstream reduction efforts are effectively matched by safe and transparent downstream handling.

Closely linked, the **Techniques of Circular Economy** section shifts the focus from treatment to valorisation. KPIs on *Recycling* and *Reuse*, ranging from *Electronic Waste Recycling Rate* to *Water Reused Internally*, encourage companies to prioritize resource loops over disposal, while the *Expected Durability of Products in Relation to Industry Average* expands the logic of circularity from waste handling to product design. Together, these indicators push companies to consider not only how waste is managed, but also how materials are conceived and reintroduced into value chains.

The broader category of **Resource Utilization** integrates energy and water as key operational inputs. *Energy Consumption* is split by scope and source, ensuring visibility over fossil versus renewable supply, while efficiency-oriented KPIs such as *Energy Savings* and *Energy Intensity* highlight performance improvements. The inclusion of *Energy Performance Gap Between As-built and As-designed*, then, reflects the relevance of bridging design expectations and actual use. On the *Water* side, metrics like *Water Intensity*, *Water Efficiency*, and *Sustainable Water Use Rate* ensure companies account for both overall withdrawals and the quality of their sourcing, recognizing water as both a scarce resource and a contextual risk factor. The *Materials* section further enriches the framework by capturing how input choices shape environmental impact. Indicators like *Low Emissioning Materials Used*, *Consumption of Renewable Materials*, and *Overall Consumption of Recycled Plastic* encourage substitution toward lower-impact resources, while *Material Efficiency* links inputs to outputs, rewarding companies that maximize productivity per unit of resource consumed. Finally, the categories *Other Sources* and *Management* broaden the scope of evaluation, with fuel and natural gas consumption KPIs addressing additional emission drivers that often escape energy balance sheets, and governance-related indicators such as *Good Practices Regarding the Use of Packaging* or *Purchases from Certified Sustainable Suppliers* showing how procurement and packaging choices contribute to resource efficiency and sustainability credibility.

Taken together, the Resources dimension moves beyond static monitoring of inputs and waste to provide a holistic view of how companies generate, use, recover, and replace resources. By combining efficiency metrics, circular economy practices, and responsible sourcing, it encourages organizations to integrate resource management into both operational strategy and long-term innovation.

Resources					
Waste Management		Techniques of Circular Economy		Resource utilization	
Waste Generation		Recycling		Energy	
Total Waste Generated	<i>Total Mass</i>	Tons of Recycled Waste	<i>Total Mass</i>	Total Energy Consumption	<i>Total MegaWatt Hours</i>
Waste Generated per Unit Produced	$\frac{\text{Total Waste Generated}}{\text{Number of Units}}$	Ratio of Recycled Waste	$\frac{\text{Recycled Waste}}{\text{Total Waste}} \times 100\%$	Energy Consumed for Scope 1	<i>Total MegaWatt Hours</i>
Percentage of Hazardous Waste	$\frac{\text{Hazardous Waste}}{\text{Total Waste}} \times 100\%$	Recycling Rate of Wastewater	$\frac{\text{Recycled Wastewater}}{\text{Total Wastewater}} \times 100\%$	Energy Consumed for Scope 2	<i>Total MegaWatt Hours</i>
Percentage of Non-Hazardous Waste	$\frac{\text{Non Hazardous Waste}}{\text{Total Waste}} \times 100\%$	Electronic Waste Recycling Rate	$\frac{\text{E.Waste Recycled}}{\text{Total E.Waste}} \times 100\%$	Total Energy Purchased	<i>Total MegaWatt Hours</i>
Metallic and Contaminated Waste	<i>Total Mass</i>	Production Waste Recycled	$\frac{\text{Recycled Waste from Production}}{\text{Total Waste from Production}} \times 100\%$	Energy Purchased for Scope 1	<i>Total MegaWatt Hours</i>
Percentage of E-Waste Generated	$\frac{\text{E.Waste}}{\text{Total Waste}} \times 100\%$	Input Materials Recycled	$\frac{\text{Recycled Input Materials}}{\text{Total Input Materials}} \times 100\%$	Energy Purchased for Scope 2	<i>Total MegaWatt Hours</i>
Rubbish Generation Rate	$\frac{\text{Rubbish Generated}}{\text{Number of Employees}}$	Reuse		Total Energy Generated	<i>Total MegaWatt Hours</i>
Amount of Effluents Generated	<i>Total Volume</i>	Tons of Reused Waste	<i>Total Mass</i>	Energy Self-Generated for Scope 1	<i>Total MegaWatt Hours</i>
Quality of Effluents Generated	<i>Score [1 ... 5]</i>	Ratio of Reused Waste	$\frac{\text{Reused Waste}}{\text{Total Waste}} \times 100\%$	Energy Self-Generated for Scope 2	<i>Total MegaWatt Hours</i>
Industrial Wastewater Generation	<i>Total Volume</i>	Water Reused Internally	<i>Total Volume</i>	Energy Efficiency	$\frac{\text{Total Generated Output}}{\text{Energy Input}}$
Waste Management		Sale of Sub-Products	<i>Score [Yes, No]</i>	Energy Intensity	$\frac{\text{Energy Input}}{\text{Total Generated Output}}$
Provision of Waste Management Plan	<i>Score [Yes, No]</i>	Expected Durability of Products in Relation to Industry Average	$\frac{\text{Products Life} - \text{Average Life}}{\text{Average Life}}$	Energy Savings	$\text{Energy Consumed Previous Year} - \text{Energy Consumed Current Year}$
Number of Wastewater Technologies Applied	<i>Number</i>			Energy Consumption from Renewable Resources	<i>Total MegaWatt Hours</i>
Waste Mitigants (Diverted from Disposal)	<i>Total Mass</i>			Renewable Energy Generation	<i>Total MegaWatt Hours</i>
Waste Generated that is Valued	<i>Total Mass</i>			Renewable Energy from External Purchase	<i>Total MegaWatt Hours</i>
Waste Generated that is Energy-Valued	<i>Total Mass</i>			Energy Consumption from Non-Renewable Fuels	<i>Total MegaWatt Hours</i>
Waste Reduction Rate	$\frac{\text{Waste Previous Year} - \text{Waste Current Year}}{\text{Waste Current Year}}$			Energy Performance Gap Between As-built and As-Designed	$\frac{\text{Actual Energy Consumption} - \text{Designed Consumption}}{\text{Designed Energy Consumption}}$
Waste Disposal and Recovery				Reduction Level the Net Embodied Energy	$\left(1 - \frac{\text{EE of New Materials}}{\text{EE of Standard Materials}}\right) \times 100\%$
Disposal Rate of Dangerous Waste	$\frac{\text{Hazardous Waste Disposed}}{\text{Total Hazardous Waste}}$			Building Energy Performance Certificate	<i>score [A, B, C, D, E, F, G]</i>
Total Waste Recovered	<i>Total Mass</i>			Heating Demand Reduction	$\text{Heating Demand Previous Year} - \text{Heating Demand Current Year}$
Total Waste Disposed of	<i>Total Mass</i>			Water	
Tons of Separate Waste	<i>Total Mass</i>			Water Consumption	<i>Total Volume</i>
Waste Transferred to Third Parties	<i>Total Mass</i>			Water Intensity	$\frac{\text{Water Input}}{\text{Total Generated Output}}$
				Water Efficiency	$\frac{\text{Total Generated Output}}{\text{Water Input}}$
				Surface Water Consumption	<i>Total Volume</i>
				Groundwater Consumption	<i>Total Volume</i>
				Consumption of Rainwater Caught	<i>Total Volume</i>
				Consumption of Non-drinking or Recycled Water	<i>Total Volume</i>
				Total Water Use Reduction	$\text{Water Consumed Previous Year} - \text{Water Consumed Current Year}$
				Industrial Water Self-Sufficiency	$\frac{\text{Internally Sourced Water}}{\text{Total Water Used}} \times 100\%$
				Sustainable Water Use Rate	$\frac{\text{Water from Sustainable Sources}}{\text{Total Water Used}} \times 100\%$

Table 8: Environmental Dimension Framework - Resources pt.1

Resources					
Waste Management		Techniques of Circular Economy		Resource utilization	
				Materials	
				Total Material Consumption	Total Mass
				Material Consumption for Products	$\frac{\text{Materials Used for Products}}{\text{Total Consumed Materials}}$
				Material Consumption for Process	$\frac{\text{Materials Used for Processes}}{\text{Total Consumed Materials}}$
				Material Consumption for Packaging/Wrapping	$\frac{\text{Materials Used for Packaging}}{\text{Total Consumed Materials}}$
				Stock Materials	Total Mass
				Number of Materials with EPDs	$\frac{\text{Input Materials with EPDs}}{\text{Total Consumed Materials}}$
				Low Emissioning Materials Used	$\frac{\text{Low Emissioning Input Materials}}{\text{Total Consumed Materials}}$
				Material Efficiency	$\frac{\text{Total Generated Output}}{\text{Materials Input}}$
				Consumption of Renewable Materials	$\frac{\text{Renewable Materials}}{\text{Materials Input}}$
				Overall Consumption of Recycled Plastic	Total Mass
				Other Sources	
				Natural Gas Consumed in Production	Total Volume
				Gas from Non-Renewable Energy	Total Volume
				Fuel Consumption	Total Volume
				Diesel Fuel Consumed by Company Cars	Total Volume
				Management	
				Good Practices Regarding the Use of Packaging	Score [Yes, No]
				Purchases from National Suppliers	$\frac{\text{Purchases from National Suppliers}}{\text{Total Purchases}} \times 100\%$
				Purchases from Certified Sustainable Suppliers	$\frac{\text{Purchases from Certified Suppliers}}{\text{Total Purchases}} \times 100\%$
				Purchases from Sustainable Suppliers	$\frac{\text{Purchases from Sust. Suppliers}}{\text{Total Purchases}} \times 100\%$

Table 9: Environmental Dimension Framework - Resources pt.2

4.4.2. Social Dimension

Access to Resources

The **Access to Food and Water** indicators overall highlight the importance of guaranteeing basic needs within the workplace. Measures such as *Access to Drinking Water* and *Water Accessibility Rate* ensure that essential services are universally available to employees, while *Food Accessibility Index* expands the focus to nutritional aspects. The cluster on *Canteen Services* then explores not only the presence of facilities but also their quality, through indicators like *Satisfaction with the Company Canteen* and *Canteens Offering a Healthy Meal*, shifting the emphasis from simple provision to employee well-being. Finally, *Food Donation* metrics link internal accessibility to broader community engagement, demonstrating how surpluses can be redirected to social value creation.

Access to Housing captures another fundamental dimension of social sustainability, where indicators like *Participation in Housing Programs* and *Long-Term Housing Stability* underline the company's role in supporting employees' life security beyond the workplace. The inclusion of affordability metrics such as *Housing Affordability Index* and *Housing Expenditure* then ensures that housing support is assessed not only by availability but also by its real economic accessibility in relation to employees' income.

The **Access to Services** cluster combines health, mobility, and social engagement, with *Provision of Medical Assistance and First Aid* and the *Health Services Accessibility Index* securing a baseline of safety and health coverage, and accessibility metrics on *Public Transportation* and *Mobility Services* stressing inclusivity and logistical ease. The broader set of *Social Services* KPIs, which ranges from the *Number of Social Action Projects* to *Expenditure in Corporate Citizenship* and *Anti-Sexual Harassment Training*, demonstrates the extent to which companies engage with communities and provide equitable support systems for their workforce.

Access to Information takes this further by emphasizing transparency and empowerment, with supplier-oriented indicators, such as *Support to Suppliers on Social Responsibility* and *Membership in Initiatives along the Supply Chain*, reinforcing the diffusion of responsible practices externally. Internally, *Access to Health Information*, *Scientific Knowledge Accessibility*, and *Information Sessions* (both frequency and participation) illustrate how knowledge sharing is institutionalized, allowing employees to make informed decisions and grow their competencies.

Lastly, **Access to Spaces** links sustainability to quality of life at work and in the community, displaying indicators such as *Provision of Open Spaces*, *Green Spaces Accessibility*, *Community Events* and *Commercial Accessibility Index* respectively reflecting environmental well-being and integration with local contexts. Interestingly, the presence of metrics such as *Internal Wellness Spaces* and *Offices Offering a Nap Room*

signals a broader and innovative understanding of workplace well-being that goes beyond functional access for embracing comfort and inclusivity.

Overall, the Access to Resources dimension combines essential provisions, affordability, accessibility, and community integration, painting a comprehensive picture of how companies can support the material and social needs of their stakeholders in ways that are both practical and equitable.

Access To Resources					
Access to Food and Water		Access to Housing		Access to Services	
Accessibility in the Workplace		Housing Arrangements		Health and Safety Services	
Access to Drinking Water	Score [Yes, No]	Participation in Housing Program	$\frac{\text{Employees in Housing Programs}}{\text{Total Eligible Employees}}$	Provision of Medical Assistance and First Aid	Score [Yes, No]
Water Accessibility Rate	$\frac{\text{Work Locations with Access to Potable Water}}{\text{Total Work Locations}}$	Long Term Housing Stability	$\frac{\text{Employees with Long Term Housing Arrangements}}{\text{Total Employees}}$	Health Services Accessibility Index	$\frac{\text{Employees with Health Insurance}}{\text{Total Employees}}$
Food Accessibility Index	$\frac{\text{Employees with Access to Meals at Work}}{\text{Total Employees}}$	Housing Affordability		Accessibility Services	
Canteen Services		Housing Affordability Index	$\frac{\text{Median Employee Income}}{\text{Median Housing Costs}}$	Level of Access to Public Transportation and Public Facilities	$\frac{\text{Locations with Access to Public Benefits}}{\text{Total Locations}}$
Presence of a Company Canteen	Score [Yes, No]	Housing Expenditure	$\frac{\text{Average Housing Costs}}{\text{Average Employees Income}}$	Mobility Service Accessibility	$\frac{\text{Employees with Company Provided Vehicle}}{\text{Total Employees}}$
Satisfaction with the Company Canteen	Likert			Accessibility (Possibility to Serve Customers Regardless of Location, Experience, Background...)	Likert
Canteens Offering a Healthy Meal	Number			Social Services	
Food Donation				Number of Social Action Projects Promoted by the Company	Number
Total Food Donated	Total Mass			Number of People Impacted by Social Actions Promoted by the Company	Number
Food Donation Rate	$\frac{\text{Food Donated}}{\text{Total Food in Excess}}$			Expenditure in Corporate Citizenship	Total Investments
				Financial Services Accessibility Index	$\frac{\text{Employees Using Company's Financial Services}}{\text{Total Employees}}$
				Legal Services Accessibility Index	$\frac{\text{Legal Consultations Provided}}{\text{Total Requests}}$
				Annual Anti-Sexual Harassment Training	Score [Yes, No]

Table 10: Social Dimension Framework - Access to Resources pt.1

Access To Resources			
Access to Information		Access to Spaces	
CSR and Supplier Engagement		Accessibility	
Support to Suppliers on Social Responsibility Consciousness-raising and Counselling	<i>Likert</i>	Provision of Open Spaces	<i>Number</i>
Membership in an Initiative that Promotes Social Responsibility along the SC	<i>Score [Yes, No]</i>	Green Spaces Accessibility	$\frac{\text{Green Space Area}}{\text{Total company Area}}$
Open Access Area for Collaboration and Knowledge Exchange	<i>Likert</i>	Community Events Held in Company's Retail Stores	<i>Number</i>
Information for Employees		Commercial Accessibility Index	$\sum \text{Stores Within 1km}$
Access to Health Information	<i>Likert</i>	Presence of Internal Wellness Spaces	<i>Score [Yes, No]</i>
General Knowledge Resources Accessibility	$\frac{\text{Employees with Access to Knowledge Sources}}{\text{Total Employees}}$	Employee Satisfaction with Local Amenities	<i>Likert</i>
Scientific Knowledge Resources Accessibility	$\frac{\text{Employees with Access to Academic Sources}}{\text{Total Employees}}$	Offices Offering a Nap Room or Equivalent to Rest	$\frac{\text{Offices Offering a Nap Room}}{\text{Total Offices}}$
Information Sessions Participation Rate	$\frac{\text{Spots Available in Information Sessions}}{\text{Participations}}$		
Information Sessions Frequency	$\frac{\text{Information Sessions Organized}}{\text{Working Days}}$		

Table 11: Social Dimension Framework - Access to Resources pt.2

Education

The **Youth Education** indicators primarily capture how companies extend their responsibility to future generations, both through internal initiatives and external community engagement. Measures such as *Presence/Strength of Community Education Initiatives* and *Organizational Support for Community Initiatives* emphasize the company's ability to foster an educational culture beyond the workplace, while *Sponsored Educational Programs Accessibility* and *Education Cost Support* demonstrate direct support for employees' families. The *Scholarships Utilization Rate* further ensures that such opportunities are not only offered but actually accessed, thereby making the initiative effective rather than symbolic. Complementing these forward-looking measures, the inclusion of *Educational Level* as part of the Work Environment provides an internal baseline of human capital, highlighting the qualification profile of employees and their readiness for professional growth.

The **Vocational Training** cluster moves closer to daily operations, with a strong emphasis on the development of skills across hierarchical levels and functions. Indicators such as *Training Hours* by employee category (executives, managers, workers) and specialized training on *Safety, Environmental, and Digital Skills* capture the breadth of investment in workforce competencies, while *Training Rate* and *Qualification Days per Employee* offer standardized metrics for benchmarking intensity. Beyond individual performance, the framework also acknowledges the collective and relational side of learning, with the SC and Employees Involvement cluster including measures like *Percentage of Employees Receiving Training* and *Security Awareness and Training*. Alongside initiatives that promote collaboration and compliance with ethical standards, these elements stress that training is not only a tool for productivity but also for responsible conduct and stakeholder engagement. Finally, the Training Management indicators provide a more strategic perspective, covering *Investments in Employee Qualification*, *Innovation Clusters*, and *Average Expenses on Training per Employee* that, together with the *Percentage of Employees who Obtained Career Development Reviews*, ensure that training is not treated as a cost but as a long-term investment in human capital, with mechanisms in place to evaluate its effectiveness and alignment with career paths.

Overall, the Education dimension creates a continuum from external support to youth and communities, through individual upskilling across employee categories, to organizational strategies that institutionalize learning and development. This layered approach ensures that companies are not only building present capabilities but also shaping the conditions for future talent and long-term social contribution.

Education			
Youth Education		Vocational Training	
Initiatives		General and Technical Skills	
Presence/Strenght of Community Education Initiatives	<i>Likert</i>	Delivered Training Hours	<i>Total Hours</i>
Organizational Support for Community Initiatives	<i>Likert</i>	Training Capacity (in Hours per Year)	<i>Total Hours</i>
Sponsored Educational Programs Accessibility	$\frac{\text{Available Education Programs}}{\text{Employee s' Children Eligible}}$	Training Rate	$\frac{\text{Total Training Hours}}{\text{Total Number of Employees}}$
Education Cost Support	$\frac{\text{Average Educational Support Funding}}{\text{Average cost for Education}}$	Number of Training Hours for Executives	<i>Total Hours</i>
Scholarships Utilization Rate	$\frac{\text{Total Scholarships Awarded}}{\text{Total Scholarships Available}}$	Number of Training Hours for Managers	<i>Total Hours</i>
Work Environment		Number of Training Hours for Employees	<i>Total Hours</i>
Educational Level	$\frac{\text{Employees with Diploma}}{\text{Total Number of Employees}}$	Number of Training Hours for Intermediates	<i>Total Hours</i>
		Number of Training Hours for Workers	<i>Total Hours</i>
		Number of Training Hours Provided to Employees by Gender	<i>Total Hours</i>
		Number of Hours of Professional Technical Training	<i>Total Hours</i>
		Number of Hours of Language Training	<i>Total Hours</i>
		Number of Hours of Safety and Environmental Training	<i>Total Hours</i>
		Number of Hours of Occupational Health and Safety Training	<i>Total Hours</i>
		Number of Hours of Sales and Key Account Management Training	<i>Total Hours</i>
		Number of Hours of Quality Management Training	<i>Total Hours</i>
		Number of Hours of Content Marketing Training	<i>Total Hours</i>
		Number of Hours of Software Training	<i>Total Hours</i>

Table 12: Social Dimension Framework - Education pt.1

Education			
Youth Education		Vocational Training	
		Number of Hours of Internal Logistics Training	<i>Total Hours</i>
		Number of Hours of GDPR Training	<i>Total Hours</i>
		Number of Hours of Digital Skills Training	<i>Total Hours</i>
		Qualification Days per Employee per Year	<i>Total Hours</i>
		SC and Employees Involvement	
		Number of Workers/Stakeholders Trained	<i>Number</i>
		Percentage of Employees Receiving Training	$\frac{\text{Trained Employees}}{\text{Number of Employees}} \times 100\%$
		Security Awareness and Training	$\frac{\text{Personnel Receiving Security Training}}{\text{Number of Employees}} \times 100\%$
		Employee Awareness of The Importance of Compliance with Competition Legislation	<i>Likert</i>
		Support to Suppliers on Social Responsibility Consciousness-raising and Counselling	<i>Likert</i>
		Membership in an Initiative that Promotes Social Responsibility along the SC	<i>Score [Yes, No]</i>
		Teamwork and Multidisciplinary Collaboration	<i>Likert</i>
		Number of Improvement Suggestions per Employee	$\frac{\text{Suggestions from Employees}}{\text{Number of Employees}}$
		Training Management	
		Investments in Employee Qualification	<i>Total Investments</i>
		Established Innovation Clusters	<i>Number</i>
		Average Expenses on Training per Employee p.a.	$\frac{\text{Investments in Training}}{\text{Number of Trained Employees}}$
		Percentage of Employees who Obtained Career Development Reviews	$\frac{\text{Employees Receiving a Career Review}}{\text{Number of Employees}} \times 100\%$

Table 13: Social Dimension Framework - Education pt.2

Work and Income

The **Economic Well-being** indicators establish a foundation of fairness and equity in remuneration. Metrics such as *Lowest Paid Worker Compared to the Minimum Wage* and the *Ratio of Basic Salary of Men to Women* provide transparency on wage compliance, while the explicit measure of *Gender Pay Gap* ensures that disparities are not only acknowledged but also monitored across categories and geographies. Alongside equity, supplementary indicators such as *Overtime Payment Rate*, *13th and 14th Salary*, and *Employee Income Growth Rate* reflect the broader structure of compensation, highlighting whether wages evolve fairly over time and whether additional benefits are integrated into employee earnings.

The section on **Work Standards** broadens the focus from pay to the conditions under which work is performed. Baseline protections, including the *Absence of Child Labour* and *Absence of Forced Labour*, represent fundamental social safeguards, while the *Presence of an Explicit Code of Conduct* institutionalizes these commitments within governance structures. Indicators such as *Talent Development and Retention* or *Employee Satisfaction Rate* link compliance with a positive workplace culture, complemented by measures on *Volunteering* that capture the company's contribution to civic engagement, while the inclusion of *Promotion Rate* bridges standards and career progression showing whether internal mobility and recognition are effectively supported. Within *Welfare and Benefits*, the framework captures the extent to which companies go beyond legal compliance to enhance employees' well-being, including *Company Contributions to Pensions*, *Possibility of Parental Leave*, *Access to SmartWorking* and *Paid Absence for Sickness* that all reflect the flexibility and security employees can count on. The percentage of workers *Covered by Collective Bargaining Agreements* and *Receiving Career Development Reviews* adds a collective and developmental dimension, while innovative benefits such as those linked to sustainability projects highlight the company's effort to align employee incentives with broader strategic goals. The *Work Environment* cluster then links employee experience to occupational safety and comfort, including indicators such as *Level of Engagement* and *Indoor Air Quality*, complemented by physical parameters like *Lighting*, *Thermal Comfort*, and *Absence of Toxic Products*, monitored to ensure that productivity is matched by healthy conditions. Satisfaction-based metrics related to temperature and humidity further stress the subjective dimension of workplace quality, showing that employee perceptions matter alongside objective measures. Finally, *Work Attendance* and *Employee Turnover* provide operational insights into workforce stability and efficiency. Attendance-related indicators, from *Work Attendance Rate* to *Zero Absence Rate* and *Overall Work Efficiency versus Effort*, demonstrate whether employees are consistently present and whether their output justifies the invested time, while turnover measures offer a longer-term perspective, with breakdowns by age, gender, and nationality, as well as forward-looking metrics like *Percentage of Workforce to Retire in the Next 5 Years*.

Complementary indicators on *Temporary Employees*, *New Hires*, and *Mandays Lost per Employee* provide a full picture of workforce dynamics, clarifying whether companies can maintain resilience and continuity in human resources.

Overall, the Work and Income dimension integrates equity, working standards, benefits, environment, and workforce stability into a single structure. By combining basic safeguards with advanced welfare practices and detailed turnover metrics, it ensures that companies are assessed not only on the fairness of pay but also on the broader conditions that determine long-term employee well-being and organizational sustainability.

Work and Income			
Economic Well-being		Work Standards	
Wage Compliance and Equity		Standards and Conditions	
Lowest Paid Worker, Compared to the Minimum Wage	$\frac{\text{Lowest Wage}}{\text{Minimum Wage by Law}} \times 100\%$	Overall Work Conditions	Likert
Ratio of Basic Salary of Men to Women by Employee Category	$\frac{\text{Average Men Salary}}{\text{Average Women Salary}}$	Workers' Freedom to Terminate their Employment within the Prevailing Limits	Likert
Gender Pay Gap by Employee Category and/or Country	$\frac{\text{Male Average Pay} - \text{Female Average Pay}}{\text{Male Average Pay}}$	Absence of Working Children Under Legal Age	Score [Yes, No]
Supplementary Wage		Absence of Forced Labour	Score [Yes, No]
Overtime Payment Rate	$\frac{\text{Overtime Pay per Hour}}{\text{Regular Pay per Hour}} \times 100\%$	Presence of Explicit Code of Conduct (CoC) protecting Workers'	Score [Yes, No]
13th and 14th Salary (% from Gross Wage)	$\frac{13\text{th} + 14\text{th}}{\text{Total Gross Wage}} \times 100\%$	Number of Disciplinary Actions	Number
Employee Income Growth Rate	$\frac{\text{Current Average Payroll} - \text{Previous Average Payroll}}{\text{Previous Average Payroll}} \times 100\%$	Number of Employees Involved in Volunteering	Number
		Hours that Company's Employees Participated in Volunteering	Total Hours
		Talent Development and Retention	Likert
		Employee Satisfaction Rate	Likert
		Responsibility for Products and Processes	Likert
		Promotion Rate	$\frac{\text{Employees Promoted}}{\text{Total Employees}}$
		Welfare and Benefits	
		Social Benefits provided	Number
		Company Contribution (Pensions)	$\frac{\text{Contribution to Pension}}{\text{Salary}} \times 100\%$
		Employee Welfare	Likert
		Possibility of Having Parental Leave	Score [Yes, No]

Table 14: Social Dimension Framework - Work and Income pt.1

Work and Income			
Economic Well-being		Work Standards	
		Access to Work Flexibility Systems in the Event of Parent Leave	Score [Yes, No]
		Possibility of Working in SmartWorking	Score [Yes, No]
		Work-Life Balance	Likert
		Paid Absence for Sickness	Score [Yes, No]
		Employee Satisfaction Rate for Benefits Received	Likert
		Percentage of Employees Covered by Collective Bargaining Agreements	$\frac{\text{Covered Employees}}{\text{Number of Employees}} \times 100\%$
		Percentage of Employees Receiving Regular Performance and Career Development Reviews	$\frac{\text{Employees Receiving Career Reviews}}{\text{Number of Employees}} \times 100\%$
		Percentage of Employees who Earned a Benefit for their Participation in a Sustainable Project	$\frac{\text{Employees Receiving Sustainable Benefit}}{\text{Number of Employees}} \times 100\%$
		Delocalization and Migration Number of Individuals that Resettle due to Organization	Number
		Percentage of Workforce Covered by Health Insurance by Law	$\frac{\text{Insured Employees}}{\text{Number of Employees}} \times 100\%$
		Percentage of Cost of Medical Premiums for Employees Covered by the Company	$\frac{\text{Average Covered Cost}}{\text{Average Total Cost}} \times 100\%$
		Work Environment	
		Level of Employee Engagement	Likert
		Lighting and Visual Comfort	Likert
		Indoor Air Quality	Likert
		Absence of Toxic Products	Score [Yes, No]
		Time Outside of Thermal Comfort Range	Total Hours
		Satisfaction Degree with Temperature	Likert
		Satisfaction Degree with Humidity Level	Likert

Table 15: Social Dimension Framework - Work and Income pt.2

Work and Income			
Economic Well-being		Work Standards	
		Work Attendance	
		Work Attendance Rate	$\frac{\text{Attended Days}}{\text{Workdays in the Period}} \times 100\%$
		Number of Hours Worked per Week	$\frac{\text{Total Worked Hours}}{\text{Number of Employees}}$
		Number of Overtime Hours per Week	$\frac{\text{Total Overtime Hours}}{\text{Weeks per Year}}$
		Zero Absence Rate	$\frac{\text{Employees with No Absence}}{\text{Number of Employees}}$
		Overall Work Efficiency versus Effort	$\frac{\text{Units Produced}}{\text{Hours Worked}}$
		Employee Turnover	
		Employee Turnover Rate	$\frac{\text{Number of Separations}}{\text{Number of Employees}} \times 100\%$
		Overall Turnover Number	Number
		Overall Turnover Number by Age	Number
		Overall Turnover Number by Gender	Number
		Overall Turnover Number by Nationality	Number
		Employee Average Age	$\frac{\sum \text{Employee's Age}}{\text{Number of Employees}}$
		Average Period of Employment	$\frac{\sum \text{Employee's Employment Days}}{\text{Number of Employees}}$
		Percentage of Workforce to Retire in next 5 Years	$\frac{\text{Soon Retiring Employees}}{\text{Number of Employees}} \times 100\%$
		Number of Temporary Employees	Number
		Change in the Number of Employees under Permanent or Fixed-Term Contracts over 3 Years	$\frac{\text{Recently Retired Employees}}{\text{Number of Employees}} \times 100\%$
		Change in Permanent Contract Turnover Rate	$\frac{\text{Current Turnover Rate} - \text{Previous Turnover Rate}}{\text{Previous Turnover Rate}} \times 100\%$
		Hiring from Permanent Contract	$\frac{\text{Permanent Hiring}}{\text{Total Hiring}} \times 100\%$
		New Hires in the Last Year	Number
		Percentage of Employees Leaving p.a. / Total Employees	$\frac{\text{Employees Retiring}}{\text{Number of Employees}} \times 100\%$
		Percentage of Trained Employees Leaving p.a. / Total Employees	$\frac{\text{Trained Employees Retiring}}{\text{Number of Employees}} \times 100\%$
		Number of Mandays Lost per Employee p.a.	$\frac{\text{Lost Mandays}}{\text{Number of Employees}}$
		New Jobs Creation	Number

Table 16: Social Dimension Framework - Work and Income pt.3

Health and Healthcare

The **Physical Health** cluster focuses on occupational safety and accident prevention, with core indicators such as *Total Accidents*, *Number of Accidents per Hour Worked*, and *Number of Days Due to Work Accidents* capturing the immediate frequency and severity of workplace incidents, and more advanced measures like *Workers Accident Severity* and *Rate of Occupational Accidents with Serious Consequences* contextualizing their impact on overall well-being and productivity. Complementary indicators such as *Work-Related Death Rate* and *Days Lost due to Injuries* provide a longer-term view of the costs of unsafe conditions, both for employees and for the organization. Supporting this monitoring, the *Health and Safety Management* group introduces measures of organizational commitment and preventive culture, with KPIs like *Provision of Protective Gear*, *Introduction of OSHA Standards*, and *Preventive Measures and Emergency Protocols* that highlight structural safeguards and employee's protection. *Employees Safety Rate*, *Suppliers Safety Rate*, and *Consumers Safety Rate* broaden the scope to the entire value chain, while the inclusion of *Sickness Rate* and the *Provision of Supportive Measures for Employees with Critical Health Issues* ensures that performance is not restricted to accident prevention but also extends to health maintenance and employee care. The *Environmental Quality and Control* indicators recognize that working conditions depend not only on processes but also on the environment in which they take place, and therefore displays indicators such as *Noise Pollution Reduction Level* and *Application of Indoor Air Quality Strategies*, that directly link occupational safety to environmental management, as well as *Time Outside Indoor Air Quality Range* that quantifies exposure to suboptimal conditions, thereby connecting daily experience with long-term health outcomes.

Finally, the **Mental Health** column introduces a complementary set of KPIs that address well-being beyond physical safety. *Engagement in Prevention and Organization Efforts to Strengthen Community Health* emphasize proactive approaches, while *Employees Having Access to Health Programs* measures the inclusivity and economic affordability of support services. The *Assistance and Illness* cluster then monitors utilization and effectiveness, through indicators such as *Mental Programs Utilization Rate* and *Employee Assistance Program Effectiveness*, alongside the *Rate of Reported Mental Health Issues*, which makes visible an area often underreported yet critical to overall sustainability.

Together, these clusters integrate safety, prevention, environment, and mental well-being into a coherent assessment that combines reactive measures (accidents, sickness, injuries) with preventive and support-oriented KPIs. The framework ultimately ensures that organizations are evaluated not only for their ability to manage risks but also for their capacity to foster long-term health and resilience among employees and stakeholders.

Heath and Healthcare			
Physical Health		Mental Health	
Accidents and Injuries		Prevention Initiatives	
Total Accidents	Number	Engagement in Prevention	Likert
Number of Accidents per Hour Worked	$\frac{\text{Total Number of Accidents}}{\text{Total Hours Worked}}$	Organization Efforts to Strengthen Community Health	Likert
Number of Days Due to Work Accidents	Number	Employees Having Access to Health Programs	Number
Workers Accident Severity	$\frac{\text{Days Due to Work Accidents}}{\text{Total Number of Accidents}}$	Assistance and Illness	
Rate of Occupational Accidents with Serious Consequences	$\frac{\text{Serious Accidents}}{\text{Total Accidents}} \times 100\%$	Mental Programs Utilization Rate	$\frac{\text{Employees Using Mental Health Programs}}{\text{Number of Employees}}$
Number of Accidents Ascribed to the Organization	Number	Rate of Reported Mental Health Issues	$\frac{\text{Reported Cases of Mental Health Issues}}{\text{Number of Employees}}$
Total Injuries	Number	Employee Assistance Program Effectiveness	Likert
Injuries With Serious Consequences	Number		
Injuries Resulting in Death	Number		
Days Lost due to Injuries	Number		
Work Related Death Rate	$\frac{\text{Deadly Accidents}}{\text{Number of Workers}} \times 100\%$		
Health and Safety Management			
Provision of Protective Gear	Score [Yes, No]		
Engagement in Prevention	Likert		
Introduction of OSHA Standards	Score [Yes, No]		
Preventive Measures and Emergency Protocols for Pesticide & Chemical Exposure	Number		
Consumers Safety Rate	$\frac{\text{Consumer Incidents Ascribed to Products}}{\text{Number of Sold Units}} \times 100\%$		
Suppliers Safety Rate	$\frac{\text{Suppliers Incidents}}{\text{Number of Suppliers}} \times 100\%$		
Employees Safety Rate	$(1 - \frac{\text{Employees Incidents}}{\text{Number of Employees}}) \times 100\%$		
Sickness Rate	$\frac{\text{Days Lost for Sickness}}{\text{Total Worked Days}} \times 100\%$		
Provision of Supportive Measures for Employees Working with Critical Health Issues	Score [Yes, No]		
Environmental Quality and Control			
Noise Pollution Reduction Level	$\text{Previous Noise Pollution} - \text{Current Noise Pollution}$		
Application of Indoor Air Quality Strategies	Score [Yes, No]		
Time Outside Indoor Air Quality Range	Total Hours		

Table 17: Social Dimension Framework - Health and Healthcare

Human Rights

The **Physical Health** cluster focuses on occupational safety and accident prevention, with core indicators such as *Total Accidents*, *Number of Accidents per Hour Worked*, and *Number of Days Due to Work Accidents* capturing the immediate frequency and severity of workplace incidents, and more advanced measures like *Workers Accident Severity* and *Rate of Occupational Accidents with Serious Consequences* contextualizing their impact on overall well-being and productivity. Complementary indicators such as *Work-Related Death Rate* and *Days Lost due to Injuries* provide a longer-term view of the costs of unsafe conditions, both for employees and for the organization. Supporting this monitoring, the Health and Safety Management group introduces measures of organizational commitment and preventive culture, with KPIs like *Provision of Protective Gear*, *Introduction of OSHA Standards*, and *Preventive Measures and Emergency Protocols* that highlight structural safeguards and employee's protection. *Employees Safety Rate*, *Suppliers Safety Rate*, and *Consumers Safety Rate* broaden the scope to the entire value chain, while the inclusion of *Sickness Rate* and the *Provision of Supportive Measures for Employees with Critical Health Issues* ensures that performance is not restricted to accident prevention but also extends to health maintenance and employee care. The Environmental Quality and Control indicators recognize that working conditions depend not only on processes but also on the environment in which they take place, and therefore displays indicators such as *Noise Pollution Reduction Level* and *Application of Indoor Air Quality Strategies*, that directly link occupational safety to environmental management, as well as *Time Outside Indoor Air Quality Range* that quantifies exposure to suboptimal conditions, thereby connecting daily experience with long-term health outcomes.

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Human Rights			
Equality, Diversity and Inclusion		Voice	
Gender Representation		Employee Rights	
Ratio of Male and Female	$\frac{\sum \text{Male Employees}}{\sum \text{Female Employees}}$	Workers' Freedom to Terminate their Employment Within the Prevailing Limits	Score [Yes, No]
Percentage of Gender for Managerial Staff	$\frac{\text{Employees by Gender}}{\text{Total Managerial Staff}} \times 100\%$	Presence of Unions Within the Organization	Score [Yes, No]
Percentage of Gender for Technical Staff	$\frac{\text{Employees by Gender}}{\text{Total Technical Staff}} \times 100\%$	Participation of Employees' Representatives in Decisions Affecting Working Conditions	Score [Yes, No]
Percentage of Gender for Employees	$\frac{\text{Employees by Gender}}{\text{Total Number Employees}} \times 100\%$	Membership in Associations or Organizations	Score [Yes, No]
Gender Composition Rate for Permanent Contract	$\frac{\text{Employees by Gender}}{\text{Total Permanent Contracts}} \times 100\%$	Freedom of Expression at the Company	Likert
Gender Composition Rate for Fixed-Term Contract	$\frac{\text{Employees by Gender}}{\text{Total Fixed Term Contracts}} \times 100\%$	Possibility of Having a Complaint System	Score [Yes, No]
Gender Composition Rate for Full-Time Contract	$\frac{\text{Employees by Gender}}{\text{Total Full Time Contracts}} \times 100\%$	Number and Duration of Strikes and Lockouts	Total Hours
Gender Composition Rate for Part-Time Contract	$\frac{\text{Employees by Gender}}{\text{Total Part Time Contracts}} \times 100\%$	Percentage of Employees Covered by Bargaining Agreements	$\frac{\text{Covered Employees}}{\text{Total Employees}} \times 100\%$
Racial Representation		Possibility to Raise Concerns Anonymously	Score [Yes, No]
Ratio of Ethnic Groups	$\frac{\text{Employees by Ethnic Group}}{\text{Total Employees}} \times 100\%$	Employee Engagement	
Percentage of Racial/Ethnic Group for Managerial Staff	$\frac{\text{Employees by Ethnic Group}}{\text{Total Managerial Staff}} \times 100\%$	Level of Employee Engagement	Likert
Percentage of Racial/Ethnic Group for Technical Staff	$\frac{\text{Employees by Ethnic Group}}{\text{Total Technical Staff}} \times 100\%$	Annual Meetings Held with Community Members	Number
Percentage of Racial/Ethnic Group for Employees	$\frac{\text{Employees by Ethnic Group}}{\text{Total Number Employees}} \times 100\%$	Employee Contribution to the Group's Sustainability Profile	$\frac{\text{Initiatives Suggested by Employees}}{\text{Total Initiatives}} \times 100\%$
Number of Employees by State	Number	Acceptance of Digital Support	Likert

Table 18: Social Dimension Framework - Human Rights pt.1

Human Rights			
Equality, Diversity and Inclusion		Voice	
Workforce Diversity		Satisfaction and Acceptance	
Number of Employees per Age Group	Number	Public Satisfaction	Likert
Number of Employees with Professional Education	Number	Satisfaction with Payment Method	Likert
Number of Employees with Technical Institute Education	Number	Market Acceptance	Likert
Number of Employees with Other Secondary School Education	Number	Stakeholder Engagement and Feedback	
Number of Employees with Humanity Degrees	Number	Number of Complaints Filed through Given Channels	Number
Number of Employees with Other Lower Titles	Number	Engagement with Affected Communities or with their Representatives Directly	Score [Yes, No]
Inclusivity		Affected Communities are Allowed to Use Anonymous Channels to Raise Concerns	Score [Yes, No]
Strenght of Organizational Procedures to Integrate Migrant Workers into the Community	Likert	Engagement with Customers or with their Representatives Directly	Score [Yes, No]
Availability of Relevant Organization's Information in Employees' Spoken Language	Likert	Number of Complaints Received from Consumers	Number
Equal Opportunities and Non-Discrimination	Likert		
Local Community Involvement	Likert		
Social Compatibility	Likert		
Percentage of People with Disabilities	$\frac{\text{Employees with Disabilities}}{\text{Total Employees}} \times 100\%$		
Participation			
Rate of Employees that are Shareholders	$\frac{\text{Shareholder Employees}}{\text{Total Number Employees}} \times 100\%$		
Internal Participation Rate	$\frac{\text{Employees Participatng in Internal Activities}}{\text{Total Number Employees}} \times 100\%$		

Table 19: Social Dimension Framework - Human Rights pt.2

Security

The **Public Security** indicators capture an organization's preparedness to protect employees and stakeholders from immediate risks, including both basic safeguards such as the *Existence of Fire-Fighting Equipment and Emergency Exits* and the *Provision of Medical Assistance and First Aid*, that overall represent essential compliance measures, and *Social Security Rate* and *Public Safety Training Completion*, that instead indicate a more structural and preventive approach. Operational performance is further reflected in the *Mean Time to Respond* to incidents and in measures like *Working Time with Hazardous Activities* or *Number of Incidents Ascribed to the Organization*, which ensure that companies remain accountable for risks directly linked to their operations.

The **Food Safety** dimension, though narrower, is equally important as it directly affects employees' health and trust in internal services, with the only indicator of *Contamination Incident Rate* in company canteens used to provide a clear, outcome-based metric that links daily organizational practices to tangible well-being results.

Environmental Security expands the scope of protection to natural and infrastructural risks, displaying indicators such as the *Number of Environmental Management Measures* and *Employee Safety Training Coverage* that together show how organizations integrate environmental risk management into their daily operations. *Fire Equipment Maintenance Compliance* and *Fire Detection Time* measure preparedness to respond to emergencies effectively and, combined with the former, collectively stress the importance of both preventive systems and responsive capacity.

Finally, **Cyber Security** acknowledges the increasingly critical role of data protection in overall corporate security. The *Data Management* cluster, with KPIs like *Data Privacy*, *Accessibility of Open Data Sets*, and *Compliance with Data Protection Regulations*, ensures that companies balance transparency with confidentiality, while *Personnel Security Screening* adds an additional safeguard by assessing vulnerabilities linked to human factors. The *Cyber Security Incidents* cluster then tracks both resilience and responsiveness through measures such as *Time to Diagnose*, *Rate of Cybersecurity Incidents*, and *Number of Data Breaches Notified to Authorities*, which are then complemented by indicators like *Vulnerability Management*, *Access Control*, and *Risk Assessment Vulnerability* that reflect the extent to which risks are systematically identified, mitigated, and monitored over time.

By combining prevention, monitoring, and response-oriented KPIs, the Security dimension integrates physical, environmental, health-related, and digital safeguards into a coherent structure, ultimately ensuring that companies address the full spectrum of risks to employees, stakeholders, and assets by embedding security as a cornerstone of sustainable and responsible operations.

Security							
Public Security		Food Safety		Environmental Security		Cyber Security	
Assistance and Provision		Company Canteen		Management Involvement		Data Management	
Existence of Fire-Fighting Equipment and Emergency Exits	Score [Yes,No]	Contamination Incident Rate	$\frac{\text{Contaminations Reported}}{\text{Total Meals Served}} \times 100\%$	Number of Environmental Management Measures	Number	Data Privacy	Likert
Provision of Medical Assistance and First Aid	Score [Yes,No]			Employee Safety Training Coverage	$\frac{\text{Employees Trained in Disaster Management}}{\text{Total Employees}} \times 100\%$	Accessibility of Open Data Sets	$\frac{\text{Accessible Open Data Sets}}{\text{Total Maintained Data Sets}} \times 100\%$
Social Security Rate	$\text{Employer Contribution Rate} + \text{Employee Contribution Rate}$			Fire Equipment Maintenance Compliance	$\frac{\text{Completed Maintenance Operations}}{\text{Mandatory Maintenance Operations}} \times 100\%$	Compliance with Data Protection Regulations	Score [Yes,No]
Public Safety Training Completion	$\frac{\text{Completions of Public Safety Training}}{\text{Total Employees}} \times 100\%$			Fire Detection Time	Average Time to Detection	Personnel Security Screening	$\frac{\text{Screened Employees}}{\text{Total Employees}} \times 100\%$
Mean Time to Respond	$\frac{\text{Average Response Time}}{\text{Total Number of Incidents}}$					Cyber Security Incidents	
Risk and Accidents						Time to Diagnose	$\frac{\text{Hours for Diagnosis}}{\text{Number of Issues}}$
Working Time with Hazardous Activities on-site	Total Hours					Rate of Cybersecurity Incidents	$\frac{\text{Cybersecurity Incidents}}{\text{Total Operations}} \times 100\%$
Number of Incidents Ascribed to the Organization	Number					Number of Data Breaches Notified to Authorities	Number
						Vulnerability Management	$\frac{\text{Mitigated Vulnerabilities}}{\text{Total Found Vulnerabilities}} \times 100\%$
						Access Control	$\frac{\text{Entry Points Accessed Without Authorization}}{\text{Total Access Points}} \times 100\%$
						Risk Assessment Vulnerability	$\frac{\text{Remediated Vulnerabilities}}{\text{Total Vulnerabilities}} \times 100\%$

Table 20: Social Dimension Framework - Security

4.4.3. Governance Dimension

Ethics

The **Crimes** dimension addresses different areas of corporate misconduct, starting from *Environmental Compliance and Issues*, where the *Number of Complaints regarding Missing Environmental Documentation* and the *Number of Reported Environmental Issues/Disputes* provide a measure of transparency, while the *Total Amount of Environmental Fines and Penalties* captures the severity of breaches. Moving to *Labor Practices*, the focus is placed on fundamental rights through the *Presence of Forced Labor at the Organization* or the *Presence of Working Children Under Legal Age*, alongside indicators assessing the organization's ability to manage internal incidents and its exposure to unresolved legal proceedings. The *Corruption* category highlights whether the company cooperates with external entities and implements preventive programs, while the *Number of Confirmed Incidents of Corruption or Bribery* serves as a concrete outcome measure, and *Other Litigation Payments* adds a residual view of broader legal risks.

The **Policies** dimension captures how organizations formalize sustainability and governance commitments. Under *Environmental Sustainability*, elements such as the *Establishment of Environmental Protection Standards*, the *Presence of Certified Environmental Management Systems*, and the *Presence of Publicly Available Documents on Sustainability* show structural alignment with recognized frameworks, while complementary measures like the *Provision of Building Energy Model* or the *Share of Trips by Train* extend the scope to operational practices. *Social Sustainability* instead emphasizes community engagement, where *Charity Donations Rate*, *Charity Contributions*, and participation in national or local initiatives highlight a company's integration with its social context. In *Corporate Governance and Composition*, indicators range from local hiring policies and compliance with property rights to whistle-blower protection and anti-corruption commitments, while *Work Environment* focuses on compliance with occupational standards and the strength of policies designed to prevent late payments.

The **Conflict of Interests** cluster reflects how organizations mitigate integrity risks, with the *Percentage of Revenues in Regions with IT Corruption Index Below 6.0* providing an external risk exposure measure, and *The Organization Cooperates with Internal/External Entities to Prevent Corruption* together with the *Training Completion Rate* reflecting active internal management. Moreover, the inclusion of the *Entity is Subjected to Legal Requirements with Regard to Protection of Whistleblowers* and the *Investigators are Separate from Management Involved in Detection of Corruption* serve as guarantees of impartiality in the detection and handling of corruption cases.

Lastly, **Data Handling** emphasizes the protection of both employee and customer information. In *Employee Related Data*, indicators such as the *Retention of Birth*

Certificate, Passport, or Other Original Worker Documents or the *Employee Data Accuracy Index* relate to basic rights and data reliability, while the *Employee Data Security Breach Rate* and the *User Accounts Measure* reflect vulnerability in IT systems. For *Customers Related Data*, attention shifts to external trust, with the *Customers Data Security Breach Rate* and the *Customer Privacy Training for Employees* acting as concrete markers of an organization's responsibility in safeguarding sensitive information.

Overall, the Ethics dimension consolidates compliance, preventive policies, and data protection into a coherent set of KPIs, ensuring that organizations are not only legally accountable but also proactive in fostering integrity, transparency, and responsible conduct across all areas of operation.

Ethics							
Crimes		Policies		Conflict of Interests		Data Handling	
Environmental Compliance and Issues		Environmental Sustainability		Risk Mitigation		Employee Related Data	
Number of Complaints regarding Missing Environmental Documentation	Number	Establishment of Environmental Protection Standards	score [Yes, No]	Percentage of Revenues in Regions with IT Corruption Index Below 6.0	$\frac{\text{Revenues from Non Corrupted Countries}}{\text{Total Revenues}}$	Retention of Birth Certificate, Passport, or Other Original Worker Documents	score [Yes, No]
Number of Reported Environmental Issues/Disputes	Number	Presence of Certified Environmental Management Systems	score [Yes, No]	The Organization Cooperates with Internal/External Entities to Prevent Corruption	score [Yes, No]	Employee Data Accuracy Index	$\frac{\text{Verified Records}}{\text{Total Employee Records}} \times 100\%$
Total Amount of Environmental Fines and Penalties	Total Costs	Presence of Publicly Available Documents on Sustainability	score [Yes, No]	Training Completion Rate	$\frac{\text{Employees Trained on Conflict of Interest}}{\text{Total Employees}} \times 100\%$	Employee Data Security Breach Rate	$\frac{\text{Breaches Involving Employees Data}}{\text{Total Employees Records}} \times 100\%$
Number of Environmental Violations	Number	Number of Actions to Improve Sustainability Performance	Number	Entity is Subjected to Legal Requirements with Regard to Protection of Whistleblowers	score [Yes, No]	User Accounts Measure	$\frac{\text{Employees with Access to Shared Accounts}}{\text{Total Employees}} \times 100\%$
Labor Practices		Documentation of Products	score [Yes, No]	Investigators are Separate from Management Involved in Detection of Corruption	score [Yes, No]	Customers Related Data	
Presence of Forced Labor at the Organization	score [Yes, No]	Provision of Building Energy Model	score [Yes, No]			Customers Data Security Breach Rate	$\frac{\text{Breaches Involving Customer's Data}}{\text{Total Customers Records}} \times 100\%$
Presence of Working Children Under Legal Age	score [Yes, No]	Share of Trips by Train	$\frac{\text{Trips by Train}}{\text{Total Trips}} \times 100\%$			Customer Privacy Training for Employees	$\frac{\text{Trained Employees Handling Customer Data}}{\text{Total Employees}} \times 100\%$
Fines, Penalties, and Compositions for Internal Incidents (including Harassment)	Total Costs	Social Sustainability					
Number of Outstanding Legal Proceedings for Late Payments	Number	Charity Donations Rate	$\frac{\text{Total Donations}}{\text{Net Profit}}$				
Corruption		Charity Contributions	Total Donations				
The Organization Cooperates with Internal/External Entities to Prevent Corruption	score [Yes, No]	Strength of Policies in Place to Protect the Rights of Communities	Likert				
The Organization Carries Out Anti-Corruption Programs	score [Yes, No]	Strength of Policies in Place to Protect Cultural Heritage	Likert				
Number of Confirmed Incidents of Corruption or Bribery	Number	Participation To Social Initiatives at National and Local Level	score [Yes, No]				
Others		Number of Organizations Funded through Company's Grant Programs	Number				
Other Litigation Payments	Total Costs	Employees Actively Involved in Grantmaking	Number				
Corporate Governance and Composition:							
		Strength of Policies on Local Hiring Preferences	$\frac{\text{Local Hires}}{\text{Total Hires}} \times 100\%$				
		Level of Integrated Design Policies	$\frac{\text{Projects Conforming to Policies}}{\text{Total Projects}} \times 100\%$				
		Level of Compliance with Property Rights	$(1 - \frac{\text{Compliance Incidents}}{\text{Total Audits}}) \times 100\%$				
		Level of Effective Site Selection	$\frac{\text{Sites Selected according to Criteria}}{\text{Total Sites Selected}} \times 100\%$				
		Documented Statements or Procedures to Prevent Engagement or Complicity in Anticompetitive Behaviour	score [Yes, No]				
		Presence of Policies on Protection of Whistle-Blowers	score [Yes, No]				
		Presence of Policies on Anti-Corruption or Anti-Bribery consistent with UN	score [Yes, No]				
		Presence of Policies with respect to Animal Welfare	score [Yes, No]				
Work Environment:							
		Notification of Occupational Accidents, Incidents, and Diseases	score [Yes, No]				
		Compliance Level with Lighting Design Standards	$\frac{\text{Number of Compliant Parameters}}{\text{Total Required Parameters}} \times 100\%$				
		Compliance Level with Daylight Design Requirements	$\frac{\text{Number of Compliant Parameters}}{\text{Total Required Parameters}} \times 100\%$				
		Compliance Level with Acoustic Standards	$\frac{\text{Number of Compliant Parameters}}{\text{Total Required Parameters}} \times 100\%$				
		Strenght of Policies to Prevent Late Payments	Likert				

Table 21: Governance Dimension Framework – Ethics

Lobbying and Political Contributions

The **Lobbying and Political Contributions** dimension addresses how organizations engage in political activity, covering both the mechanisms that ensure compliance with legal and ethical standards and the scale of resources devoted to influencing decision-making. Under *Compliance and Auditing*, indicators such as the *Compliance Rate* and the *Audit Rate* highlight the extent to which lobbying activities are aligned with legal requirements and systematically reviewed, while the *Contributions* cluster captures the financial side, including the *Value of Political Contributions*, the *Amount of Internal and External Lobbying Expenses*, and more specific forms such as the *Amount Paid for Membership in Lobbying Associations* and *In-Kind Political Contributions Made*. Together, these KPIs provide a balanced picture of both the monetary extent of political engagement and the degree of control and oversight applied to such activities.

Lobbying and Political Contributions	
Lobbying and Political Contributions	
Compliance and Auditing	
Compliance Rate	$\frac{\text{Lobbying Activities Compliant with Law}}{\text{Total Lobbying Activities}} \times 100\%$
Audit Rate	$\frac{\text{Lobbying Activities Audited Annually}}{\text{Total Lobbying Activities}} \times 100\%$
Contributions	
Value of Political Contributions	Total Contributions
Amount of Internal and External Lobbying Expenses	Total Contributions
Amount Paid for Membership in Lobbying Associations	Total Costs
In-Kind Political Contributions Made	Total Contributions

Table 22: Governance Dimension Framework - Lobbying and Political Contributions

Communication

The **Communication** dimension emphasizes both stakeholder engagement and the quality of disclosure practices, showing how organizations build trust through openness and reliable reporting. Within *Stakeholders Awareness*, indicators such as the *Number of Meetings with Community Stakeholders* and the *Engagement of the Organization to Present Yearly Communication on Progress* reflect the degree of transparency towards external actors, while the *Employee Awareness of the Importance of Compliance with Competition Legislation* and the *Awareness Degree of Public with Eco-Industrial Development* underline how knowledge is shared internally and externally. From a *Supply Chain* perspective, measures like the *Proximity to Suppliers and Consumers* and the *Daily Communication Uptime* capture the effectiveness of both relational integration and operational continuity, while *Transparency and Reporting* provides a more systematic view, where the *Environmental Information Accuracy Rate*, the *Environmental Information Availability Rate*, and the *Accessibility of Open Data Sets* together with the *Quality of Open Data* ensure the robustness of information disclosure. Complementary indicators such as *Transparency in Lobbying Activities*, the *Audit Compliance Score*, and the *Greenwashing Incident Rate* assess credibility, while responsiveness is captured through the *Customer Inquiries Response Rate* and accountability reinforced by *Product Traceability* and the *Audit and Accountability Record Review*, which link transparency not only with reporting quality but also with measurable oversight practices.

Communication	
Information Asymmetry	
Stakeholders Awareness	
Number of Meetings with Community Stakeholders	Number
Employee Awareness of The Importance of Compliance with Competition Legislation	Likert
Awareness Degree of Public with Eco-Industrial Development	Likert
Engagement of the Organization to Present Yearly Communication on Progress	score [Yes, No]
Supply Chain	
Proximity to Suppliers and Consumers	Likert
Daily Communication Uptime	$\frac{\text{Available Communication Time}}{\text{Total Daily Time}} \times 100\%$
Transparency and Reporting	
Environmental Information Accuracy Rate	$\frac{\text{Verified Data Points}}{\text{Reported Data Points}} \times 100\%$
Environmental Information Availability Rate	$\frac{\text{Publicly Available Data Points}}{\text{Collected Data Points}} \times 100\%$
Accessibility of Open Data Sets	$\frac{\text{Accessible Open Data Sets}}{\text{Total Maintained Data Sets}} \times 100\%$
Quality of Open Data	Likert
Transparency in Lobbying Activities	$\frac{\text{Lobbying Activities Fully Disclosed}}{\text{Total Lobbying Activities}} \times 100\%$
Audit Compliance Score	Average Audit Score
Greenwashing Incident Rate	$\frac{\text{Greenwashing Incidents}}{\text{Total Environmental Claims}} \times 100\%$
Customer Inquiries Response Rate	$\frac{\text{Responded Inquiries}}{\text{Total Inquiries Received}} \times 100\%$
Product Traceability	Likert
Audit and Accountability Record Review	$\frac{\text{Audit Records Reviewed in the Year}}{\text{Total Planned Reviews}} \times 100\%$

Table 23: Governance Dimension Framework – Communication

Risk Management

Within **Strategic Risk**, the subdimension of *Innovation and Technology Development* reflects the organization's ability to anticipate change and sustain competitiveness, with indicators such as *Investments in Innovations and New Technologies* and *Number of Digital Transformation Initiatives Fully Implemented* that show the scale and maturity of innovation efforts, and measures like the *Technology Development Involvement* and the *Payback Time of Technological Solution Packages* highlighting the balance between resource allocation and efficiency of returns. Complementary aspects, including the *Euro of Investments for Recycling Processes*, *Security Budget*, and *Continents where the Company Invested in Renewable Energy Projects*, expand the scope towards circularity, resilience, and global reach. The link between innovation and sustainability becomes more explicit in *Sustainability and Environmental Impact*, where the *Sustainable Innovations Rate* and the *% of New Environmentally Sound Product Development* are combined with the *% of Production Sites with Environmental Certifications*, emphasizing not only compliance but also the proactive creation of environmentally friendly solutions. Added to this, the *Share of Audited Suppliers Regarding Social Responsibility* and the *Number of Eco-Labelled Products* show how sustainability criteria extend to supply chains and product portfolios. In *Market Position and Competitive Strategy*, competitive advantage is reflected in the *Sustainable Business Ideas Generated* and the *Response to Environmental Product Requests Rate*, supported by the *Number of Sustainable Patents Applications* and the *Projects Assigned to R&D*, which all demonstrate how innovation translates into tangible and marketable outputs. Finally, the *Governance* cluster reinforces the integrity of decision-making through the *Disclosure of the Functions that are Most at Risk of Corruption*, *Supplier Compliance Rates* on both ethics and sustainability, and the *Risk Assessment Frequency*, while also considering transparency with the *Engagement of the Organization to Present Yearly Communication on Progress* and contributions such as the *Euro for Investments in the Community*.

Turning to **Operational Risk**, the *Compliance and Safety* cluster stresses adherence to standards, with indicators ranging from the *Regular and Documented Payment of Workers* to the *Hazardous Material Incident Rate* and the *Building Energy Performance Certificate Level*, further supported by systems such as the *Presence of Certified Environmental Management Systems* and the *C&A Completion Assessment* that ensure certified compliance. The *SC Management* cluster then expands on operational resilience, combining the *Percentage of Payments Aligned with Standard Payment Terms*, *Forecasting Accuracy*, and *Scrap Reduction Rate* with the adoption of *Lean Management* and *Poka-Yoka* practices, alongside preventive measures like *Maintenance Measure*. Lastly, *Errors Management* addresses quality and reliability issues, with *Human Error Rate* and *Production Rework Rate* linked to process discipline through the *Process Compliance Rate*. Structural aspects of stability are captured by the *Digital System Downtime Rate* and

System and Information Integrity, while corrective capacity is ensured through the *Root Cause Analysis Completion Rate* and the *Product Recall Rate due to Misuse*.

Taken together, these dimensions provide a structured overview of both strategic adaptability and operational robustness, linking innovation, sustainability, governance, and process discipline into a coherent framework for risk mitigation.

Risk Management			
Strategic Risk		Operational Risk	
Innovation and Technology Development		Compliance and Safety	
Investments in Innovations and New Technologies	$\frac{\text{Total Investments}}{\text{Total Investments}} \times 100\%$	Regular and Documented Payment of Workers	$\frac{\text{On Time Payments}}{\text{Total Payroll Transactions}} \times 100\%$
Number of Digital Transformation Initiatives Fully Implemented	$\frac{\text{Number}}{\text{Number}} \times 100\%$	Hazardous Material Incident Rate	$\frac{\text{Incidents due to Hazardous Materials}}{\text{Operations with Hazardous Materials}} \times 100\%$
Technology Development Involvement	$\frac{\text{Resources for Tech Development}}{\text{Total Resources}} \times 100\%$	Building Energy Performance Certificate Level	Score [A, B, C, D, E, F, G]
Payback Time of Technological Solution Packages	$\frac{\text{Investments in Technologies}}{\text{Annual Savings through Technologies}} \times 100\%$	Presence of Certified Environmental Management Systems	Score [Yes, No]
Euro of Investments for Recycling Processes	$\frac{\text{Total Investments}}{\text{Total Investments}} \times 100\%$	C&A Completion Assessment	$\frac{\text{New Systems Implemented after Certification and Accreditation}}{\text{Total Implemented Systems}} \times 100\%$
Investments in Technologies Rate	$\frac{\text{Investments in Technology}}{\text{Total Investments}} \times 100\%$	System and Service Acquisition	$\frac{\text{Acquisition Contracts Including Security Requirements}}{\text{Total Acquisition Contracts}} \times 100\%$
Investment in Technology Transfer or Research	$\frac{\text{Total Investments}}{\text{Total Investments}} \times 100\%$	SC Management	
Security Budget	$\frac{\text{Investments in Cybersecurity}}{\text{Total Investments}} \times 100\%$	Percentage of Payments Aligned with Standard Payment Terms	$\frac{\text{On Time Payments}}{\text{Total Number of Payments}} \times 100\%$
Continents where the Company Invested in Renewable Energy Projects	$\frac{\text{Number}}{\text{Number}} \times 100\%$	Number and Length of Power Outages	Total Hours
Sustainability and Environmental Impact		Forecasting Accuracy	$\frac{\text{Actual Demand} - \text{Forecasted Demand}}{\text{Actual Demand}} \times 100\%$
Number of Actions to Improve Sustainability Performance	$\frac{\text{Number}}{\text{Number}} \times 100\%$	Scrap Reduction Rate	$\frac{\text{Previous Scrap Rate} - \text{Current Scrap Rate}}{\text{Previous Scrap Rate}} \times 100\%$
Sustainable Innovations Rate	$\frac{\text{Sustainable Innovations}}{\text{Total Innovations}} \times 100\%$	Adoption of Lean Management	Score [Yes, No]
% of New Environmentally Sound Product Development	$\frac{\text{Environmentally Friendly Products}}{\text{Total Products}} \times 100\%$	Adoption of Poka-Yoka	Score [Yes, No]
% of Production Sites with Environmental Certifications	$\frac{\text{Sites with Certifications}}{\text{Total Sites}} \times 100\%$	Maintenance Measure	$\frac{\text{Components Undergoing Maintenance as Scheduled}}{\text{Total Components}} \times 100\%$
Ratio of Investments to IT on Total Sales	$\frac{\text{Investments in IT}}{\text{Total Sales}} \times 100\%$	Errors Management	
Investments in Energy Savings	$\frac{\text{Total Investments}}{\text{Total Investments}} \times 100\%$	Human Error Rate	$\frac{\text{Errors due to Employees}}{\text{Total Hours Worked}} \times 100\%$
Share of Audited Suppliers Regarding Social Responsibility	$\frac{\text{Audited Suppliers on CSR}}{\text{Total Number of Suppliers}} \times 100\%$	Production Rework Rate	$\frac{\text{Reworked Units}}{\text{Total Units Produced}} \times 100\%$
Number of Eco-Labelled Products	$\frac{\text{Number}}{\text{Number}} \times 100\%$	Process Compliance Rate	$\frac{\text{Operations Compliant with SOP}}{\text{Total Operations Reviewed}} \times 100\%$
Market Position and Competitive Strategy		Digital System Downtime Rate	$\frac{\text{Total Downtime Hours}}{\text{Total Operating Hours}} \times 100\%$
Sustainable Business Ideas Generated	$\frac{\text{Number}}{\text{Number}} \times 100\%$	Root Cause Analysis Completion Rate	$\frac{\text{Completed Root Cause Analyses}}{\text{Total Issues}} \times 100\%$
Response to Environmental Product Requests Rate	$\frac{\text{Environmental Products Released}}{\text{Environmental Products Requested}} \times 100\%$	Product Recall Rate Due to Misuse	$\frac{\text{Recalls due to Misuse}}{\text{Total Number of Recalls}} \times 100\%$
Euro of Investments for the Quality of Products	$\frac{\text{Total Investments}}{\text{Total Investments}} \times 100\%$	System and Information Integrity	$\frac{\text{Resolved System Vulnerabilities}}{\text{Total System Vulnerabilities}} \times 100\%$

Table 24: Governance Dimension Framework - Risk Management pt.1

Risk Management			
Strategic Risk		Operational Risk	
Number of Sustainable Patents Applications	Number		
Number of Sustainable Patents Applications Filled Last Year	Number		
Number of Active Sustainable Patents	Number		
Number of Projects Assigned to R&D	Number		
Numer of Resources Engaged in R&D	Number		
Governance			
Number of Functionalities/Services Unlocked due to Sustainable Practices	Number		
Disclosure of the Functions that are Most at Risk of Corruption	Score [Yes,No]		
Euro for Investments in the Community	Total Investments		
Engagement of the Organization to Present Yearly Communication on Progress	score [Yes,No]		
Risk Assessment Frequency	$\frac{\text{Risk Assessment Operations}}{\text{Days per Year}}$		
Supplier Screening	$\frac{\text{Screened Suppliers}}{\text{Total Suppliers}} \times 100\%$		
Supplier Compliance Rate - Ethics	$\frac{\text{Compliant Suppliers}}{\text{Total Suppliers}} \times 100\%$		
Supplier Compliance Rate - Sustainability	$\frac{\text{Sustainable Suppliers}}{\text{Total Suppliers}} \times 100\%$		

Table 25: Governance Dimension Framework - Risk Management pt.2

5 Analysis of a Real-World Digital Solution

5.1. Introduction

Following the development of a comprehensive framework for corporate sustainability assessment, which could deeply address all facets and levels of environmental, social, and governance dimensions, this chapter introduces the second core theme of the thesis: the role of digitalization in enhancing sustainability performance.

Leveraging technologies such as big data analytics, artificial intelligence (AI), the Internet of Things (IoT), and cloud computing, digitalization has profoundly reshaped business models, operational processes, and decision-making dynamics across multiple sectors, becoming synonymous with efficiency and success. With origins rooted in the 20th century and an evolution that continues to shape the present, digitalization has become a pervasive element in modern economic and social systems, transforming the way organizations manage information, optimize resource use, and interact with stakeholders. With more than a half of the reviewed papers addressing this linkage, the significance of digitalization in the sustainability domain has emerged clearly, highlighting its growing role as both a catalyst for improved environmental and social outcomes and a driver of organizational transformation.

Digital transformation is now widely recognized not only as a source of economic competitiveness but also as a critical enabler for achieving broader ESG objectives, promoting inclusive growth, and fostering resilient business models capable of responding to global challenges. If it is true that important concerns remain regarding the energy consumption associated with ICT infrastructures, the environmental impact of electronic waste, the risk of exacerbating social inequalities through the digital divide, and the challenges related to data privacy and cybersecurity, it is also undeniable that digitalization has become a strategic imperative for businesses, governments, and society at large. Digital technologies have demonstrated the ability to drive operational efficiency, enable real-time resource management, and enhance transparency in corporate and supply chain processes. Indeed, applications such as smart energy management, predictive maintenance, digital tracking, and AI-driven decision-making systems have shown significant potential in supporting environmental and social objectives.

Unfortunately, as highlighted in the literature, the concrete application of digital tools for sustainability enhancement remains partly unexplored. While many studies focus on the economic benefits of digitalization, the empirical evidence regarding its environmental and social impacts is still fragmented and insufficient, calling for more integrated approaches and real-world applications capable of assessing and maximizing the positive effects while mitigating potential negative externalities.

In this context, the collaboration with Al maviva, a leading Italian group in the Information & Communication Technology (ICT) sector and a recognized promoter of digital sustainability, provides a valuable opportunity to bridge the gap between theoretical analysis and practical implementation.

5.1.1. Objectives

Leveraging the information made available about the projects and solutions already implemented by the Company, the goal of the present study is to investigate how digital technologies can concretely generate positive effects on corporate sustainability performance. With the goal to not merely explore theoretical assumptions or suggest potential correlations, but to ground the analysis in a tangible, real-world application, an original model will be developed as a methodological approach, aiming to assess the dynamic interactions between digitalization initiatives and sustainability outcomes across different dimensions.

At the core of this inquiry lies the awareness that digitalization does not produce uniformly positive effects but that, on the contrary, technologies may also generate unintended consequences, such as increased energy demand, electronic waste, or data privacy concerns. Therefore, the objective is not simply to confirm a beneficial relationship between digital tools and sustainability, but to assess their comprehensive contribution by acknowledging both benefits and potential drawbacks. Indeed, only through such an integrated evaluation digitalization can be understood and governed as a truly strategic lever for sustainable development.

Ultimately, in an era where technological innovation is increasingly recognized as a key enabler of sustainable development, this study aims to give evidence of how digital solutions can contribute not only to more accurate measurement but also to the effective improvement of environmental, social, and governance (ESG) outcomes. The investigation of Al maviva's practices and the development of applied analytical tools will be therefore instrumental in demonstrating the concrete ways through which digitalization can enhance sustainability performance and in validating the role of technologies as strategic levers for achieving a more resilient and successful corporate future.

5.2. Company Overview

5.2.1. History and Evolution

Founded in 2005 in through the acquisition of the Finsiel Group from Telecom Italia by the COS Group, Al maviva was established with the ambition of becoming a reference point for digital transformation in Italy. Building upon the technological heritage of Finsiel, historically considered one of the country's most important Information Technology players, Al maviva immediately positioned itself as a leader in supporting key sectors of the national economy through the implementation of advanced ICT solutions.

The early years of the Group were characterized by the consolidation of its presence in traditional sectors such as public administration, transportation, and finance, followed by a rapid expansion of its service portfolio toward more specialized fields. Leveraging on continuous investments in innovative technologies and integrated digital platforms, Al maviva set out from the beginning to address the increasingly complex needs of businesses and institutions facing the challenges of globalization and the digital economy.

Driven by a strategic vision oriented toward internationalization and diversification, Al maviva progressively expanded its operational footprint beyond national borders, undertaking its first initiatives already in the very first year following the creation of the Group. Above all, the company achieved a strong presence in Latin America, with significant operations in Brazil, Colombia, and the Dominican Republic, focusing primarily on customer relationship management (CRM) services and digital solutions tailored to local market demands.

Between 2007 and 2010, Al maviva strengthened its role within Italy, becoming a partner of reference for large digitalization projects promoted by public institutions and large enterprises. The Group actively contributed to the modernization of infrastructures and services in areas such as mobility, health, agriculture, justice, and public finance, often leading complex and highly innovative initiatives aimed at improving efficiency, transparency, and citizen engagement.

From 2011 onward, the company intensified its investment in emerging technologies and, recognizing the transformative potential of cloud computing, big data analytics, and the Internet of Things (IoT), began integrating these solutions into its service offerings. Through constant investment in research and development, Al maviva consolidated its position at the forefront of the Italian ICT sector and began to play a growing role in the development of smart cities, sustainable mobility, and intelligent infrastructure projects, anticipating the growing demand for sustainable urban mobility and infrastructure. The 2015-2018 period marked a further phase of diversification and innovation, with the Group launching several strategic programs

focused on artificial intelligence (AI), cybersecurity, and blockchain, reinforcing its ability to offer advanced digital ecosystems tailored to complex organizational needs.

The year 2021 marked a significant milestone in the growth trajectory of Al maviva, with the successful stock market quotation of Al mawave, subsidiary born in 2006 and specialized in Artificial Intelligence (AI), natural language processing (NLP), and big data analysis. Listed on the Euronext Growth Milan market in March 2021, Al mawave's initial public offering (IPO) represented not only a financial success but also a strategic affirmation of Al maviva's commitment to technological innovation and market leadership in emerging digital sectors. Contextually, the operation marked a further step toward consolidating Al maviva's strategy of combining digital transformation with sustainable and responsible innovation, reinforcing its role as a catalyst for economic, technological, and social development in Italy and beyond [160].

Today, Al maviva is a global player operating across five continents, with over 45,000 employees and a diversified offering that spans digital transformation, customer engagement, smart services, and sustainable innovation. Remaining firmly anchored to its Italian roots while pursuing a strategy of continuous international growth, the Group continues to play a leading role in shaping the future of digitalization and sustainability, contributing to the competitiveness, resilience, and inclusiveness of the economic and social systems it serves.

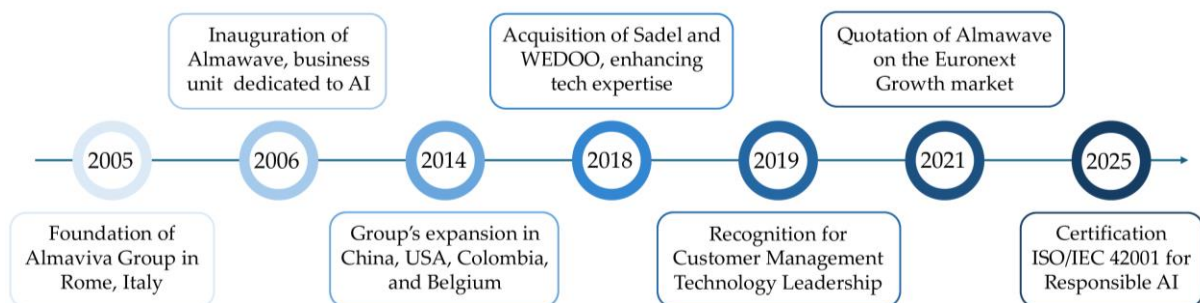


Figure 21: Al maviva's History and Milestones

5.2.2. Sustainability Commitment and Progress

Sustainability represents a central pillar in Al maviva's corporate strategy, reflecting the Group's commitment to aligning technological innovation with principles of environmental protection, social inclusion, and responsible governance. Over time, Al maviva has progressively strengthened its sustainability practices, integrating ESG factors into its operations and decision-making processes, and positioning itself as a leader in promoting a responsible digital transition.

A first structured approach toward sustainability emerged in the second half of the 2010s, when Al maviva recognized the necessity of embedding social and

environmental considerations into its technological evolution. This orientation culminated in 2019, when sustainability was formally integrated into the Group's corporate strategy, marking a decisive step in aligning business growth with sustainable development objectives.

In the following years, Al maviva launched several initiatives to operationalize its ESG commitments, among which the *Giotto Digital Ecosystem* and the *Giotto Insight Hub ESG & Sustainability*, two platforms designed to combine technological innovation with measurable environmental and social impacts. These initiatives provide integrated solutions for resource optimization, emissions reduction, and enhanced corporate responsibility, embodying Al maviva's vision of digital sustainability.

From an environmental standpoint, Al maviva has demonstrated substantial and continuous progress in minimizing its ecological footprint, reflecting a strategic commitment to integrating sustainability into all aspects of its operations. In 2023, the Group reached a significant achievement by covering almost 100% of its energy requirements through renewable sources, a goal supported by the transition to sustainable cloud infrastructures and the continuous enhancement of its environmental and energy management systems, certified according to ISO 14001 and ISO 50001 standards.

On the social front, Al maviva has implemented numerous programs to promote diversity, equity, and inclusion within its workforce. The Group actively fosters gender equality, hybrid working models, and employee well-being, and it has obtained relevant certifications in occupational health and safety. Particular attention is also given to employee development through continuous training programs and initiatives aimed at strengthening internal engagement and community involvement.

From a governance perspective, Al maviva has progressively aligned its corporate practices with the highest standards of transparency, accountability, and ethical conduct. ESG objectives have been incorporated into top management's performance evaluation and remuneration systems, ensuring that sustainability considerations are integrated at the highest levels of strategic planning and operational execution. Furthermore, the Group's commitment to responsible innovation is reflected in its participation in major initiatives such as the United Nations Global Compact and the *Fondazione per la Sostenibilità Digitale*, through which it actively promotes the development of sustainable digital practices.

In addition to internal advancements, Al maviva has contributed to external sustainability projects through its technological expertise, guided by a vision of supporting organizations, communities, and institutions in their transition toward more sustainable, resilient, and inclusive models of development. Key initiatives include solutions for smart mobility (*MOOVA*), telemedicine platforms, smart agriculture programs (*Rural to Digital*), and intelligent water and energy management

systems, all aimed at fostering resilience, inclusiveness, and environmental stewardship [160].

Overall, Almagora's path toward sustainability illustrates a coherent and continuous evolution, driven by the conviction that digital transformation and sustainable development must proceed hand in hand. By responsibly leveraging advanced technologies and proactively engaging with global ESG objectives, the Group today stands as a prominent actor in promoting a more sustainable, inclusive, and innovative future. This ongoing commitment was further confirmed on May 29, 2025, when Almagora received the ESG Recognition from DNV, an international certification that attests to the company's structured and transparent approach to environmental, social, and governance management. As only the second organization worldwide to obtain this distinction, Almagora has strengthened its positioning as a benchmark for ESG excellence, affirming the robustness of its sustainability strategy on both a national and international scale [161].

5.2.3. Responsible Digital Transformation

Almagora's approach to innovation is deeply rooted in the concept of responsible digital transformation, a vision that recognizes technology not merely as an end in itself, but as a powerful enabler of sustainable, inclusive, and ethical development. In an increasingly interconnected world, where the impacts of digitalization permeate every sector of society and the economy, Almagora promotes the idea that digital evolution must proceed hand in hand with environmental protection, social equity, and responsible governance.

The notion of responsible digital transformation stems from the awareness that technological innovation can generate profound positive effects, such as improved efficiency, accessibility, and quality of services, but also carries inherent risks associated with increased energy consumption, wider digital divides, data privacy threats, and potential socio-economic inequalities. As a result, Almagora's strategy is oriented toward maximizing the beneficial impacts of digitalization while systematically identifying, monitoring, and mitigating its potential negative externalities.

Almagora's approach also responds to a broader shift in economic and institutional paradigms, driven by the need to reconcile technological progress with environmental sustainability, social equity, and the evolving expectations of stakeholders in both the public and private sectors. In a global context increasingly defined by complexity, uncertainty, and ecological fragility, digital transformation is no longer optional but the way in which it is pursued has become critically important. Almagora embraces this responsibility by placing transparency, accountability, and sustainability at the

core of its innovation model, implying not only technical excellence but also careful reflection on the social consequences of digital systems, the empowerment of individuals, and the safeguarding of future generations' needs.

This vision is deeply embedded in Almagora's corporate mission, which aspires to act as an enabler of change for public institutions, private enterprises, and communities. The Group's activities are guided by a strong sense of ethical commitment and by the awareness that innovation must be inclusive, accessible, and mindful of long-term implications. As a consequence, continuous engagement with civil society, research networks, and international institutions become pivotal, while digitalization is no longer regarded as a temporary strategic choice but rather as a foundational cultural orientation that shapes long-term vision, values, and organizational identity.

5.2.4. Projects and Solutions

To explore the tangible effects of Almagora's commitment to responsible digital transformation, the following section presents a selection of projects that exemplify how the Group leverages advanced technologies to generate positive sustainability outcomes. By translating strategic principles into operational solutions, these projects offer valuable insights into the practical implementation of digital sustainability, highlighting real-world use cases where innovation supports environmental conservation, social inclusiveness, and ethical governance.

Environmental Sustainability

In an era where environmental resilience has become a strategic priority, Almagora stands at the forefront of applying digital technologies to mitigate ecological degradation and promote resource efficiency. From water conservation and energy optimization to emissions reduction and circularity, the company leverages IoT, data analytics, and cloud infrastructures to transform environmental management into a predictive, intelligent process. The following solutions illustrate how Almagora's digital innovation directly contributes to the achievement of global environmental targets, particularly the Sustainable Development Goals (SDGs) related to climate action, clean water, and responsible consumption.

- **Smart water management:** a platform that supports the optimization of the Integrated Water Service by leveraging IoT technologies for real-time monitoring of networks and pipelines, and advanced data analytics to detect water losses and manage system pressure. Fully interoperable with existing systems, the solution provides decision support functionalities to guide interventions, contributing to water conservation and infrastructure sustainability.

- **Smart energy management:** a platform designed to use centralized energy monitoring technologies to enable data-driven rationalization of energy consumption in public and private buildings. Allowing for the acquisition, analysis, and control of operational data across multiple structures, SEM transforms energy data into actionable insights that drive reductions in consumption and emissions.
- **Giotto digital ecosystem:** a modular and interoperable system that combines cloud technologies and cybersecurity platforms to offer customized digital solutions across sectors and alignment with the Sustainable Development Goals (SDGs). By integrating innovative and mature technologies within a single ecosystem, Al maviva provides organizations with tools to optimize resource use, minimize environmental impacts, and comply with regulatory frameworks.
- **Giotto OnChain Notarization SaaS:** an innovative blockchain-based solution developed to certify the authenticity and integrity of digital assets while reducing the ecological footprint associated with traditional blockchain systems. Through energy-optimized algorithms specifically developed by Al maviva, the platform minimizes power consumption and plays a pivotal role in carbon footprint certification initiatives, supporting ESG strategies aligned with the European Green Deal. The solution was recognized among the 20 most innovative use cases by the European Blockchain Regulatory Sandbox in 2023.
- **Agri Data Value:** a project funded under the Horizon Europe program and aimed at promoting sustainable agricultural practices by utilizing big data platforms and data analytics technologies. The initiative aims to optimize resource management, improve productivity, and advance climate-smart farming techniques, supporting the sustainability and resilience of the agri-food sector through technological innovation.
- **MOST – National Center for Sustainable Mobility:** a national research initiative coordinated by the Politecnico di Milano and involving 49 organizations, including universities, the National Research Council (CNR), and major industrial players. Through its participation and the sharing of expertise in smart mobility solutions, electric and hydrogen propulsion systems, and digital monitoring infrastructures, Al maviva supports the advancement of clean, inclusive, and efficient mobility systems in line with national and European environmental objectives.

Social Sustainability

Al maviva's vision of sustainability extends beyond ecological impact to embrace human well-being, equity, and access to essential services. Guided by the principles of inclusivity, innovation, and care, the company develops digital solutions that enhance

healthcare delivery, expand educational opportunities, and foster workforce development across diverse communities. These initiatives reflect a commitment to social progress through technology, supporting the construction of a more inclusive, resilient, and human-centred society in line with international frameworks such as the UN 2030 Agenda.

- **OncologIA:** a healthcare innovation project developed to enhance oncology care through artificial intelligence, machine learning, and Digital Twin technologies. Funded by Regione Puglia and the EU, the project delivers a cloud-based platform that supports personalized treatment planning, complication prediction, and follow-up strategies, based on territorial healthcare resource availability.
- **mySMARTdiary:** an AI-powered application designed to support patients and therapists in the treatment of eating disorders, leveraging on digital technologies to offer personalized therapeutic support, reduce clinical workload, and enable more human-centered care. By combining clinical data processing with emotional awareness tools, the project demonstrates how digital solutions can have a tangible social and psychological impact, improving care continuity and emotional well-being.
- **National Telemedicine Platform:** a platform developed in partnership with Engineering and aimed at supporting the centralized governance and monitoring of regional telemedicine services, aligning with Italy's National Recovery and Resilience Plan (PNRR). Its objectives include strengthening proximity care, reducing territorial disparities, enhancing healthcare accessibility and integration, and supporting dehospitalization models.
- **MOOVA Academy:** an e-learning initiative aimed at training professionals and young graduates in integrated and sustainable mobility leveraging on the collaboration with universities and public institutions and the organization of workshops and seminars.
- **Alternanza Scuola-lavoro:** an early-career training initiative aimed at bridging the gap between education and the professional world, fostering both technical and transversal skills by involving students in real projects and workplace scenarios. Since 2014, Al maviva has welcomed over 250 secondary school students, providing them with access to innovative technologies and mentorship from expert professionals.
- **Sistema Scuola-Impresa:** a collaboration program between Al maviva and 30 companies participating in the ELIS Consortium, established to align school curricula with the evolving demands of the labor market. Since 2019, the initiative has promoted structured interactions between schools and businesses through training sessions and career orientation events, with a special focus on gender inclusion and equality.

- **Almaviva Academy:** a specialized training program launched for facilitating the transition of STEM graduates under 30 into the professional world, offering them a six-week technical training aligned with industry needs, individual mentoring, and soft skill development.
- **Evolutionary Team:** a leadership development program implemented by Almaviva in 2023 to foster self-awareness and personal growth among mid- and senior-level managers, focusing on unlocking individual and collective potential through the development of evolutionary intelligences, encouraging a more inclusive, empathetic, and human-centered leadership style across the organization.

Governance Sustainability

Responsible governance lies at the core of Almaviva's digital transformation model, which emphasizes transparency, ethical conduct, and data security. By integrating advanced platforms for risk monitoring, compliance, and cybersecurity, the company not only safeguards operational integrity but also strengthens trust across its stakeholder network. The following projects therefore demonstrate Almaviva's commitment to embedding sustainability within decision-making structures, aligning corporate strategy with robust governance practices and the evolving requirements of regulatory frameworks such as the EU Digital and Data Acts.

- **JOSHUA CybeRiskVision:** an advanced Cyber Threat Intelligence platform developed to proactively identify, monitor, and mitigate cyber risks across organizations and their supply chains. Utilizing embedded automation and threat detection technologies, the platform continuously scans the digital surface for vulnerabilities and supports real-time response to potential attacks.
- **SOFIA CybeRiskVision:** a fraud detection platform powered by AI and unsupervised machine learning algorithms, designed to identify anomalies in high-volume, low-label data environments where known fraud patterns may not exist.
- **JIANO CybeRiskVision:** a modular Identity and Access Management (IAM) platform that governs user credentials and access rights within organizations, enabling Almaviva and its clients to uphold digital integrity, accountability, and access transparency.
- **GDPR Compliance Privacy:** a regulatory compliance framework developed to manage and optimize data protection processes under the EU General Data Protection Regulation (GDPR), automating privacy-related procedures and centralizing the documentation and control functions of Data Protection Officers (DPOs).

- **TEADAL Project:** a Horizon Europe research project aimed at creating federal data lakes across cloud-edge infrastructures and multi-cloud environments, with Al maviva responsible for the integration, testing, and validation of six pilot sites across Europe.
- **DMO Monitor:** a data intelligence platform that combines desk research, online sentiment analysis, and big data analytics to evaluate the sustainability practices of Italian tourism destinations.
- **Smart Station Project:** a digital infrastructure modernization program aimed at improving the management, sustainability, and accessibility of Italy's railway stations. Implemented across 140 stations and encompassing the monitoring of over 40,000 technological systems and 1,900 civil installations, the platform reduces the need for on-site maintenance, thus lowering operational costs and CO₂ emissions. The project enhances operational efficiency while ensuring greater comfort, safety, and accessibility for all users, including those with reduced mobility.
- **RETURN:** a national research and innovation initiative, coordinated by the University of Naples Federico II, aimed at building resilient communities and infrastructures through an integrated, cross-sectoral governance approach to climate risk. The project focuses on improving the understanding of multi-risk interactions, enhancing prediction, prevention, and adaptation methodologies, developing new digital technologies and models to support institutional decision-making, and reinforcing national governance capacities in disaster risk management.

5.3. The Smart Water Management Project

5.3.1. Project Selection

The decision to focus on the Smart Water Management project stems from its exemplary representation of how digital technologies can be leveraged to address critical sustainability challenges in a real-world context. Within Al maviva's broad portfolio of innovative solutions, in fact, this project stands out as a highly integrated and impactful initiative capable of improving environmental performance while generating positive ripple effects on social and governance dimensions.

This relevance is particularly evident when considering the critical state of water resource management in Italy. According to the Italian National Institute of Statistics (ISTAT), in 2022 Italy lost approximately 3.4 billion cubic meters of potable water, which is equal to 42.4% of the total volume introduced into the public distribution network and enough to supply more than 43 million people [162]. These losses are

largely attributable to aging infrastructure, with nearly 60% of pipelines exceeding 30 years of service and a significant portion surpassing 50 [163]. Most dramatically, even major urban centres are affected, with cities like Rome and Milan experiencing leakage rates of nearly 27% and 14% respectively [164].

Globally, the issue is no less critical: worldwide, an estimated 126 billion m³ of water is lost annually through leaky systems, enough to supply about 90 million people, and in many agricultural irrigation systems over 50 % of water is lost due to evaporation and leaks [165]. As of 2022, roughly half of the world's population was recognized to experience severe water scarcity for at least part of the year, and 2.2 billion people were without access to safely managed drinking water [166].

In this scenario, the Smart Water Management project represents a forward-looking response not only aligned with Italy's national priorities but also with broader international goals and, particularly, to the SDG 6 of the United Nations Agenda 2030, which calls for sustainable water and sanitation for all. By enabling continuous monitoring, early leak detection, and predictive maintenance, Al maviva's solution directly addresses environmental degradation while simultaneously improving service quality and institutional accountability. The analysis of this solution is thus intended to go beyond siloed assessments, recognizing that the three ESG dimensions are intrinsically interwoven and that digital tools can serve as powerful levers for holistic sustainability transformation.

5.3.2. Project Description

Developed in alignment with the sustainability goals outlined in the National Recovery and Resilience Plan (PNRR), and in line with the previously exposed criticalities, the Smart Water Management presents itself as a cutting-edge digital solution created by Al maviva to modernize and optimize the operations of Italy's integrated water service infrastructure. The project combines state-of-the-art technologies such as IoT, AI-based analytics, and digital twins to enable intelligent, data-driven decision-making across the entire water value chain, ultimately supporting operational efficiency and resource conservation.

At the heart of the solution lies a comprehensive Decision Support System, designed to provide real-time monitoring, anomaly detection, simulation of intervention scenarios, and dynamic performance reporting. These capabilities are powered by a continuously updated digital twin of the water infrastructure, which is constructed through the integration of live data from a network of IoT sensors deployed throughout pipelines, pumps, and reservoirs. These sensors measure key physical parameters, such as flow rates, pressure levels, and water quality, and send real-time

data to a secure, scalable cloud infrastructure, enabling seamless aggregation and processing.

This digital twin serves as a virtual mirror of the physical system, allowing operators to simulate "what-if" scenarios, anticipate failures, and plan maintenance activities in a proactive, risk-based manner. The DSS processes incoming data streams and historical trends using AI-driven logic to support forecasting, incident prioritization, and evidence-based decision-making while, in parallel, the Business Intelligence layer translates raw data into actionable sustainability indicators, made accessible through customizable dashboards that support both strategic and operational decision-making. To complete the operational cycle, the system includes an integrated Workforce Management component, which transforms analytical outputs into field-level action. Detected anomalies or critical thresholds automatically generate alerts and intervention tasks, ensuring that technicians are efficiently dispatched based on proximity, expertise, and urgency. It is thanks to this seamless coordination that service responsiveness is enhanced, downtime minimized, and both economic and environmental costs associated with inefficient maintenance routines reduced.

In essence, Smart Water Management does not merely enable monitoring but creates an intelligent, adaptive ecosystem that learns from the network, predicts its behaviour, and orchestrates resources for continuous improvement. Through its integrated use of digital technologies, it directly supports measurable progress in water conservation, public service quality, and governance transparency, aligning with both national priorities and global sustainability objectives.

The effectiveness of the solution is already evidenced by its implementation in several southern Italian regions, where over 14,000 kilometres of water networks have been successfully digitized, monitored, and optimized using this integrated approach. These deployments demonstrate the platform's operational maturity and confirm its ability to generate tangible benefits in diverse and complex infrastructure contexts.

Finally, but most importantly, the platform's modular and interoperable architecture makes it highly scalable and replicable, allowing its deployment across diverse geographical and organizational contexts, while its alignment with evolving regulatory frameworks, including the European Green Deal and national digital transition agendas, ensures not only compliance but also long-term resilience. As such, Smart Water Management positions Al maviva at the forefront of digital innovation for sustainable infrastructure, demonstrating how technology can serve as a strategic enabler of systemic change within the water sector and beyond.

6 Development of a Model for Impact Assessment

6.1. Introduction

In line with what briefly anticipated in the previous chapter, this section presents the full process through which a dedicated model was developed to analyse, interpret, and visualize the impact of digital technologies on corporate sustainability. Moving beyond conceptual ambitions, the focus now shifts toward methodological execution and, in particular, on the process adopted for developing a structured and causally coherent framework capable of linking technological interventions with measurable sustainability outcomes.

Crucially, this model was not built in the abstract but through the continuous engagement with the already introduced Smart Water Management project by Almaviva. Far from being the object of the analysis, the project served as a practical foundation and a source of inspiration throughout the development process, providing the contextual grounding and functional detail needed to reason about actual technologies, variables, and causal relationships, enabling a progressive translation of high-level sustainability concepts into tangible, interconnected model components. In this sense, Almaviva's initiative acted as a guideline for building the model, helping to reach the final objective to design a generalizable and robust structure capable of assessing how digital solutions, such as those exemplified by Almaviva, can contribute to ESG performance.

6.2. Process Development

To develop the model, structured as a multilayer causal diagram, an unconventional, bidirectional approach was ultimately adopted, proceeding simultaneously from the top down and the bottom up to ensure internal consistency and conceptual integration. This dual-directional development was not the result of a predefined methodological choice, but rather emerged naturally through the iterative and often uncertain process of building a model entirely from scratch.

From the outset, the challenge lay in designing a structure that was at once rigorous and flexible, capable of reflecting the specificity of the chosen use case, while also maintaining internal coherence and methodological soundness. With no ready-made model available that could be convincingly applied to the complexity of the scenario under analysis, the process unfolded through a series of successive trials and multiple configurations were explored and discarded before arriving at a form that proved both functionally comprehensive and conceptually stable.

The simultaneous top-down and bottom-up reasoning developed organically, revealing as the only viable way to reconcile abstract sustainability principles with the tangible technological and operational components observed in the project. Indeed, while starting from high-level sustainability dimensions alone made it difficult to translate abstract principles into concrete, technology-enabled and operational variables, beginning with the technological components provided a clear picture of capabilities but offered little guidance on where the causal paths should lead in terms of sustainability outcomes. As a result, the two perspectives had to evolve in parallel, each compensating for the limitations of the other, until a coherent and well-aligned structure naturally emerged.

Throughout this process, the ambition was twofold: to construct a model at least partly aligned with recognized frameworks and academic standards, while also creating something authentic and tailor-made for the specific objectives of the analysis. The reasons why existing models were found to be unsuitable or slightly unfitting are disparate, ranging from ones overly qualitative and descriptive, others too reductive to capture complexity, and still others too rigid or specialized to accommodate contextual flexibility. From this, the necessity of designing a new structure, one that could draw from established logic where useful, but ultimately evolve in a direction dictated by the unique requirements of the case.

In this sense, the resulting model is the product of both methodological exploration and pragmatic necessity, a synthesis of theoretical intent and grounded experimentation. What follows is a detailed account of the key phases that shaped its development, from the initial review of documentation to the progressive refinement and structuring of causal relationships.

6.2.1. Comprehensive Documentation Review

The initial phase of the model development process consisted of an in-depth review of all documentation available on the project, including both publicly accessible materials, such as those published on the company's official website, and internal files that were shared specifically for research purposes. The goal of this phase was to

establish a robust contextual understanding, capable of guiding all subsequent analytical steps with a solid foundation.

The documentation was examined with the dual intention of catching both the overarching vision of the project and its technical and operational foundations. Special emphasis was placed on understanding the rationale behind the initiative, the problems it aimed to address, the methodologies it proposed to adopt, and the expected impact across different dimensions of sustainability.

A significant portion of the review was dedicated to identifying the technological components integrated into the solution, which included IoT sensors, Work Force Management (WFM) tools, Business Intelligence systems, and a suite of analytics and reporting capabilities. Collectively, these technologies enable predictive simulations, anomaly detection, performance monitoring, and operational decision support.

The analysis also clarified the project's primary expected outcomes: reduced water losses, improved operational efficiency, enhanced early warning capabilities, and optimized resource allocation and intervention planning. Furthermore, the review provided insight into the main enabling factors, recognizable in the integration of platforms and the automation of network monitoring, as well as structural limitations, such as the challenge of achieving seamless interoperability across diverse systems and the need to manage and interpret large volumes of heterogeneous data.

6.2.2. Sustainability Impact Identification

Building on the understanding gained through the documentation review, the next step focused on identifying the project's potential sustainability impacts. The objective was to determine how the technologies and functionalities integrated into the Smart Water Management system could influence various aspects of environmental, social, and governance (ESG) performance. This was approached by systematically analyzing the expected changes in network efficiency, resource usage, service quality, and risk mitigation described in the project materials, and interpreting them through the double lens of sustainability and assessment.

The observed and anticipated effects were mapped against the second- and third-level categories of the previously defined ESG framework, which includes both environmental dimensions such as climate change mitigation, water resource optimization, and pollution reduction, social aspects such as service continuity, public health protection, and workforce safety, and governance issues related to operational transparency, responsiveness, and digital risk management.

At this stage, the classification was intentionally kept exploratory and inclusive, with the aim of capturing all plausible areas of impact, even in the absence of formal causal structures. The effects were identified both in terms of direct outcomes, such as

reduced water loss and improved early warnings, and indirect repercussions, including the enhancement of stakeholder trust through improved reporting, or the reduction of technician exposure to hazardous interventions. The goal was to comprehend all dimensions that could be at least in part impacted by the project, while however avoiding forcing an overall inclusion of all categories that would have risked making the analysis biased, distorted, and less centred on the real objective.

Although still conceptual, this mapping effort served as a critical blueprint for the model's future architecture, as it defined the initial landscape of change to be modelled, establishing a comprehensive inventory of ESG-related variables that would later populate the upper layers of the causal diagram.

6.2.3. Technological Enablers Identification

In parallel with the identification of sustainability impacts, specific attention was devoted to organizing and cataloguing the technological components integrated into the solution. While the previous phases had already highlighted their presence and general function, this step focused on systematically isolating each element and understanding its role as an enabler of change within the system. At this stage, in fact, the model had not yet been formally structured and no hierarchical layering was in place, but technologies were already recognized as the fundamental drivers of transformation, from which all subsequent causal pathways would eventually unfold.

As clarified through the documentation, technologies included IoT sensors for continuous, real-time data collection across the water network; the digital twin for providing a virtual, dynamic replica of the physical infrastructure; a Decision Support System (DSS) for guiding interventions and optimizing strategic responses; a Work Force Management (WFM) system for organizing and coordinating field activities; a cloud platform to ensure centralized, scalable data storage and access; and Business Intelligence tools for aggregating, analysing, and visualizing key performance indicators. Designed to function synergistically, these technologies supported predictive analysis, anomaly detection, operational planning, and informed decision-making, establishing the base upon which all subsequent causal relationships in the model would be built.

6.2.4. KPI Specification and Source Matching

Once the third-level sustainability dimensions were identified and linked to the project's potential areas of impact, the next phase focused on selecting the most appropriate Key Performance Indicators (KPIs) to measure those impacts. The goal of this step was to operationalize each dimension through specific, traceable metrics

capable of capturing the actual effects of technological implementation across environmental, social, and governance areas.

This selection was guided by two parallel sources: on one hand, the sustainability framework previously developed for broader application, which provided a structured reference and a wide catalogue of recognized metrics; on the other, a more targeted exploration of literature and project-specific documentation, necessary to address the particular characteristics of the Smart Water Management system. Indeed, while the original framework had been deliberately designed for flexibility and generalizability, its level of abstraction made it sometimes inadequate for a direct application to such a detailed and context-specific case. As a result, a meticulous review of technical documents, regulatory materials, and internal reports was undertaken to extract more tailored indicators that aligned with the concrete functionalities of the technologies deployed.

In the end, by cross-referencing broader theoretical standards with narrow technical insights, the selected KPIs maintained methodological consistency while directly responding to the project's operational logic and sustainability objectives, fundamentally allowing for the reconciliation of conceptual robustness with empirical specificity.

6.2.5. Individual Causal Pathway Construction

With the KPIs defined and matched to their respective third-level sustainability dimensions, the next phase focused on understanding the mechanisms through which these indicators could be influenced by the technological solutions identified earlier. The process involved the construction of individual causal pathways developed by isolating one sustainability dimension at a time and tracing a logical sequence of effects from technological enablers through intermediate variables to the final KPI.

For each dedicated graph, starting from the core technological components previously catalogued, a first tier of variables was derived and identified as those enabled by the specific features and functional properties of the technologies themselves, such as connectivity, data integration, or real-time monitoring. Then, emerging from these, variables of a more operational character, activated not by the technology alone but by the performance improvements and systemic efficiencies it made possible. These included, for instance, faster response times, fewer number of emergency interventions, and increase digital connectivity and density.

Pathways' complexity varied depending on the KPI under consideration, as, while some were influenced by a limited number of variables and followed a linear, straightforward chain, others required multiple interlinked components, forming more elaborate and branched causal networks. In all cases, arrows were used to

represent the direction of influence and the reciprocal interconnections, maintaining consistency and clarity in the visual representation.

As a whole, this phase laid a solid foundation for the subsequent integration and structuring of the model, as it ensured that each sustainability dimension could be first addressed individually and rigorously, a well-defined causal logic that linked digital inputs to measurable ESG outcomes in a transparent and traceable way, and then comprehensively.

6.2.6. Variable Classification and Standardization

Once the individual causal pathways had been constructed, a refinement phase was undertaken to consolidate and harmonize the variables included across the different diagrams. Indeed, while the causal chains had already implicitly distinguished between types of variables based on their role and origin, this step formalized that distinction to provide a consistent foundation for the successive model's layout. Two principal categories were established:

- **Digital Levers**, derived directly from the inherent capabilities of the technological tools employed and therefore including aspects such as enhanced forecasting accuracy and real-time monitoring, that would be otherwise unreachable with such precision. These variables represent the immediate value generated by digital solutions and therefore reflect their role as initial catalysts of transformation within the system.
- **Operational Outputs**, which emerge as downstream effects made possible by the enhanced functionalities and systemic improvements triggered by the technologies, such as lower response time and reduced number of emergency interventions required.

In addition to this classification, a detailed cross-comparison was conducted to examine how similar or identical concepts had been represented across different pathways. In many cases, in fact, equivalent variables had been described using different labels depending on the specific context or sustainability dimension, but the underlying meaning was exactly the same or at least easily generalizable. These inconsistencies were therefore addressed by standardizing terminology, merging duplications, and adopting unified expressions that could apply consistently across the entire model. The underlying goal was not only to ensure semantic and structural coherence, avoiding synonyms and improving quality, but also to reduce the total number of distinct variables and emphasize the recurrence of specific key mediators. As a matter of fact, the identification of these common elements indicated that many causal pathways, although developed independently for different sustainability

dimensions, are shaped by the same underlying drivers and cross-cutting mechanisms that, due to this systematic influence, had to be properly emphasized.

Rather than being isolated or dimension-specific, these recurring variables emerged as central leverage points within the system, with their modification, often enabled by technology, consistently producing ripple effects on diverse sustainability targets. Recognizing these patterns not only allowed for a more streamlined and readable representation but also offered deeper insight into the logic of intervention, pointing to which factors are most critical to address in order to generate widespread and multidimensional impact.

6.2.7. Integration into ESG-specific Macro-diagrams

In order to emphasize the recurrent mechanisms identified during the previous phase and to enhance the readability of the overall model, the individual causal pathways were subsequently consolidated into three integrated macro-diagrams, each dedicated to one of the Environmental, Social, or Governance dimensions. This step marked a shift from a KPI-specific logic to a first-level dimension-specific representation, enabling a broader view of how technologies influence sustainability performance across multiple interrelated indicators.

In constructing these macro-diagrams, the same non-redundancy policy already introduced in the previous step was taken as baseline principle, with the result that variable repetition was deliberately avoided and each concept represented by a single, standardized label. Despite playing a role in multiple pathways, each variable was introduced only once within the chart, with its multidimensional influence conveyed through the use of several directional arrows pointing toward the various downstream elements it affects. This visual strategy makes it possible to highlight the disproportionate impact certain variables exert across the model, reinforcing their role as cross-cutting mediators.

Technologies such as IoT sensors, digital twins, or DSS platforms do not generate isolated effects, but instead activate shared mechanisms that reverberate across different areas of sustainability. Representing these interactions within a unified diagram appeared therefore as the most clever and intuitive way to allow the model maintaining analytical precision while also communicating the system-level logic of transformation.

6.2.8. Vertical Layering

Following the integration of individual diagrams into ESG-specific macro-structures, the final step in organizing the model's architecture involved arranging its

components along a vertical, layered axis. This structural choice was aimed at enhancing both the clarity of logical progression and the traceability of impacts, making explicit the causal flow from technological input to sustainability outcome.

As mentioned, at the base of the structure are positioned the technologies installed within the system, namely IoT sensors, digital twins, decision support systems (DSS), workforce management platforms, cloud environments, and business intelligence tools. These components form the foundation of the model, representing the origin point of all transformative processes and defining not only the model's technological perimeter but also its potential scope of influence.

Directly above this, the second layer comprises the before-named digital levers, those functions immediately enabled by the inherent properties of technological solutions. These variables capture the direct functional output of technological deployment, abstracted from the operational context in which they would later be applied.

The third layer is populated by operational characteristics, whose activation depend on the previous layer but which reflect tangible improvements in how the system function. These elements represent the practical, day-to-day effects that arise from the enabling technological layer and therefore constitute the first joining link between technology and business operations.

In the fourth layer, the model incorporates the variables directly used in the computation of KPIs, those company-level parameters that experience direct modifications as a consequence of the preceding operational outputs. These variables constitute the first measurable level of concrete impact in sustainability terms, as they reflect observable changes in system performance directly attributable to the technologies implemented. Examples include the volume of water wasted due to network leakages (environmental dimension), the level of training required for staff to effectively use DSS platforms (social dimension), or the number of critical issues accurately identified through monitoring tools (governance dimension). Each of these reflects an outcome that can be easily and empirically monitored and managed, thus serving as a crucial link between operational improvements and formal sustainability reporting.

Above this, the fifth layer present the KPIs themselves, already selected and validated through the process of source matching and dimensional association. Each KPI act as a formal expression of sustainability performance, grounded in the variables below and aligned with the structure of the adopted ESG framework.

Finally, the top section of the model features the hierarchical ESG categories, progressing from third-level subdimensions to second-level categories, and culminating in the overarching environmental, social, and governance pillars depending on the diagram. This tiered alignment ensures that each indicator can be

directly traced to the broader strategic sustainability objectives it contributes to, enhancing visual clarity and interpretability.

6.2.9. Causal Connectivity

Once the vertical layering of the model was defined, the next step involved establishing causal linkages between variables across the different levels, a crucial passage for translating the static architecture into a dynamic model, capable of capturing the chain reactions triggered by technological implementation.

Connections were visually represented through directional arrows, which trace the influence of one variable on another while articulating the internal logic of the system. In most cases, these arrows are drawn sequentially between adjacent layers, reflecting the expected logical progression from technological input to enabling functions, operational improvements, measurable impacts, and finally to KPIs and sustainability categories. This linearity ensures in fact that each causal relationship can be interpreted within a clear framework of stepwise transformations. Nonetheless, the model also acknowledges the presence of non-linear dynamics, where certain variables exert an influence that bypasses intermediate layers and goes directly two levels upward. For example, the introduction of advanced IT infrastructure, a first-layer element, was found to directly affect the system's digital complexity, positioned in the third layer, without necessarily passing through an intermediate enabling function. This influence is indeed immediate and structural, as complexity emerges inherently from the configuration and integration of technological components within the system and doesn't depend on any characteristic property. Likewise, certain variables in the second layer, such as real-time monitoring and preventive maintenance, are shown to directly reduce the number of non-compliant water samples, a fourth-tier variables that figure inside the Water Quality KPI.

These relationships are not exceptions in the logical sense, but rather shortcuts within the system, where the effect of one variable is sometimes strong and immediate enough to skip intermediate mechanisms. Recognizing and incorporating such connections helps in fact reinforcing the model's realism, acknowledging that not all change processes follow a rigid step-by-step progression.

6.2.10. Directional Impact Indicators

To further enhance the interpretability of the model and provide immediate visual cues regarding the nature of each effect, a system of directional impact indicators was applied to the variables within the third and fourth layers. Comprising operational characteristics and impact variables, these layers represent in fact the most dynamic

part of the model, where technological implementation begins to translate into tangible, measurable outcomes. It appeared essential, therefore, to improve interpretability and immediacy of concepts by introducing a visual tool capable of clarifying not only what changes, but also how and with what implication.

Small, coloured arrows were placed adjacent to each of these variables to signal two distinct aspects. On one level, the arrow indicates the directional shift experienced by the variable, that is to say whether its value increases or decreases in response to upstream changes. On the other level, it communicates the sustainability relevance of that shift, distinguishing between outcomes that contribute positively to ESG performance and those that instead signal potential drawbacks or criticalities. As a result, a four-level classification:

- Green and upward denotes an increase associated with improvement of sustainability performances, as for example a higher number of issues correctly anticipated or resolved in advance.
- Green and downward indicates a beneficial reduction in values that reflects enhanced results, such as the fewer emergency interventions and the lower time elapsed before issues detection.
- Red and upward signals a negative increase, representing a rise in values that may hinder sustainability objectives, such as greater digital connectivity and system complexity that can elevate management challenges and cybersecurity exposure.
- Red and downward reflects an undesirable decrease in values associated with declining performance, as in the case of reduced diagnostic reliability or drop in the effectiveness of monitoring and control systems.

The goal behind the introduction of this annotation system was to provide an added interpretive layer to the model, allowing stakeholders to immediately grasp both the quantitative direction and the qualitative impact of each transformation. By integrating these indicators directly into the diagrams, in fact, the model gained greater communicative power, enabling more intuitive readings of complex pathways and reinforcing the strategic significance of each variable.

6.2.11. Path-specific Textual Descriptions

To complement the visual structure of the model and reinforce its interpretability, each KPI included in the diagrams was accompanied by a dedicated textual box positioned at the bottom of the respective pathway. These boxes provide a concise but targeted narrative explanation of the logic behind each individual path, describing how the technologies activate enabling and operational variables, and how these, in turn, produce measurable sustainability impacts.

This choice was made necessary by the previous decision to consolidate all individual causal pathways into three comprehensive ESG-specific diagrams and by the desire to avoid losing focus on the unique logic and dynamics behind each indicator. Indeed, while the rule of using multiple arrows from shared, non-repeated mediators was essential to highlight convergence and eliminate redundancy, it also led to an overly integrated structure, where numerous pathways overlapped, relied on the same drivers, and became increasingly difficult to distinguish. As a result, tracing the full sequence of transformations behind each KPI posed a significant challenge.

To mitigate the risk, path-specific descriptions were deliberately introduced as a supplementary interpretive layer, ensuring the model could remain navigable and comprehensible even in front of a further increase of structural complexity. By clearly articulating the specific mechanisms connecting technologies to each KPI, these descriptions made it possible to distinguish individual reasoning paths and to understand how each indicator was logically constructed without relying solely on the visual representation.

6.2.12. Impact Typology Classification

As final step in the model development process, a double classification system was introduced to distinguish between the different types of impacts generated by technological interventions. This decision stemmed from the key observation that not all impacts hold the same strategic weight, nor do they follow the same level of certainty or immediacy, and that treating all as equally relevant would risk misrepresenting the true structure of the system and undermining the model's ability to guide effective sustainability planning.

The first classification addressed the probability of occurrence of each observed change, allowing the model to distinguish between certain and potential impacts based on their reliability and dependence on contextual factors.

- **Potential impacts** were characterized as plausible but not guaranteed outcomes, likely to concretize under specific circumstances but with their realization dependant on additional contextual, organizational, or behavioural conditions. While these effects remain consistent with the model's logic, they can't be universally assumed and therefore require further validation, monitoring, or enabling conditions to fully manifest. To visually distinguish these outcomes within the diagrams, a yellow outline was applied to both the corresponding KPI and its associated textual description box, signalling the conditional nature and guiding the reader's attention to areas of uncertainty or opportunity.

- **Certain impacts**, on the other hand, were defined as outcomes that could be confidently expected to occur following the implementation of the project's specific technologies. These changes are typically supported by either a well-established functional relationship or by empirical evidence drawn from similar implementations, and their occurrence is not conditional on external variables but highly reliable and repeatable across different settings. Among them, a further subdivision was possible to be made based on the type of causal link:
 - **Direct impacts** were defined as those that resulted immediately and unequivocally from the introduction of a technological component, without requiring any intervening mechanisms. These effects stem directly from the intrinsic functionalities of digital solutions, such as capacity to automate tasks, collect real-time data, or process information, and do not depend on changes in user behaviour, operational procedures, or other system-level adaptations. Their causal link is clear, traceable, and typically occurring shortly after implementation, therefore earning the green outline applied to both the KPI and the pathway explanation.
 - **Indirect impacts**, by contrast, emerged through one or more intermediate layers, requiring a chain of events or interactions before becoming visible. These effects are typically mediated by organizational processes, workflow adjustments, or human decision-making, typically unfolding over longer timeframes. They should not be considered less important than the previous ones, but certainly require a broader view of system dynamics and often involve more complexity and variability in their realization. To clearly reflect their indirect and multi-step nature within the diagrams, these impacts were visually marked with a blue outline.

In addition to this causal and certainty-based classification, a second interpretive layer was introduced to account for the strategic intent behind each identified impact. Indeed, while the model captured a wide range of outcomes stemming from technological implementation, it was essential to distinguish between those that were explicitly planned and those that emerged as emergent systemic effects. Impacts were therefore categorized into two groups:

- **Core targets**, referring to the deliberate and stated objectives of the project, those impacts that were not only anticipated but actively pursued during the design and implementation phases. These outcomes are typically aligned with performance indicators that the project aimed to improve directly and measurably, including examples such as reduction of water loss through enhanced leak detection, or improvement of anomaly detection systems via predictive analytics and real-time monitoring. These targets are at the heart of the solution's functional logic and often tie to regulatory or strategic

commitments, and are therefore visually marked in the model by a solid circle, denoting their status as planned, high-priority goals.

- **Unintentional effects**, on the other hand, were defined as unintended effects that were not explicitly sought but nonetheless materialized as a result of the system’s deployment and interaction with broader operational contexts. While not central to the project’s initial mission, these impacts represent meaningful contributions to sustainability and often address dimensions that are indirectly influenced by technological or organizational changes. Examples include the reduction of technician exposure to hazardous field conditions, enabled by a shift toward preventive rather than reactive maintenance, or the increased transparency of reporting due to the integration of real-time dashboards and data-sharing tools. To reflect their unplanned yet beneficial nature, these impacts are marked in the model using a hollow coloured circle, distinguishing them visually from the explicitly targeted outcomes while still highlighting their relevance.

The introduction of these two layers of classification, respectively certainty and causality and strategic intent, was guided by the desire to greatly enhance the model’s analytical depth and practical relevance while keeping visualization clear and immediate. If on one side it is true that the same technological solutions can generate a wide range of impacts across different sustainability dimensions, it is equally undeniable that some effects carry greater deterministic significance from both a sustainability perspective and in light of the company’s strategic objectives. By making these distinctions explicit, the model avoids flattening all outcomes into a single tier of importance and instead supports a more nuanced and actionable interpretation of value creation.

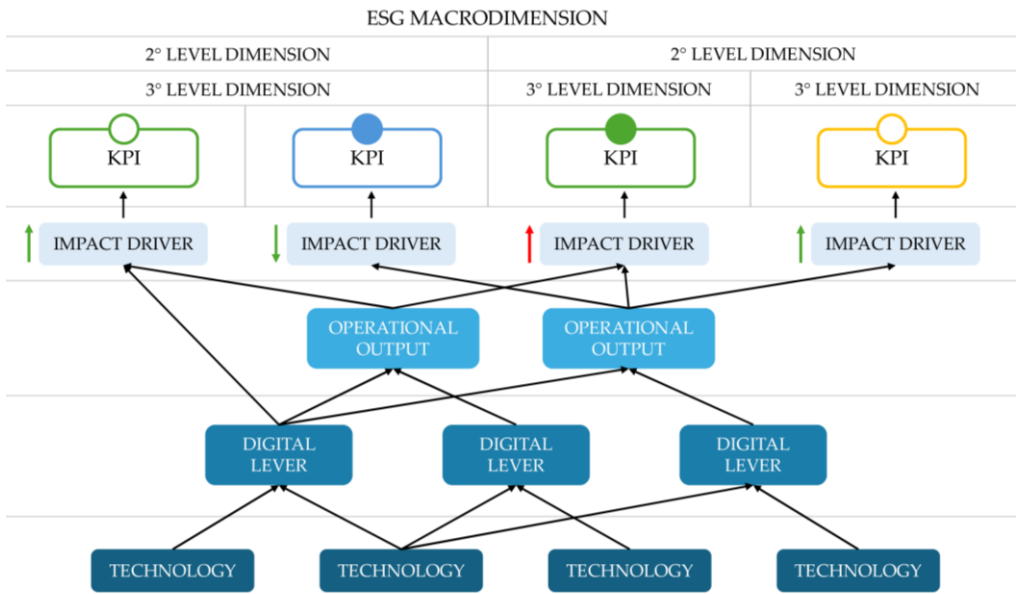


Figure 22: Map Prototype for a Generic ESG Dimension

6.2.13. Validation with Project Stakeholders

Although not formally part of the model construction process, a final and equally crucial step involved the validation of the framework through direct engagement with the company's ESG and project stakeholders. A dedicated meeting was held with individuals who had been actively involved in both the development and implementation of the Smart Water Management solution, providing them with a comprehensive view of the project's operational logic and its real-world implications.

This interaction served not much to validate the structural design of the model, which was already firmly grounded in documented evidence and causal reasoning, but rather to confirm the accuracy and relevance of the identified areas of impact and the selected KPIs. The feedback from these professionals, who touched the project with hands, proved essential in aligning the model with practical realities that written documentation alone could not fully capture. Indeed, while internal reports and technical specifications offer a necessary foundation, they often lack the contextual depth and experiential nuance that only firsthand involvement can provide.

Stakeholders also played a pivotal role in helping classify KPIs according to the two categorization frameworks previously described: certainty and causality on one side and strategic intent on the other. Their insights ensured that the impact classifications were not only logically sound, but also aligned with the organization and client's internal priorities, operational constraints, and strategic sustainability agenda.

This step of validation, although external to the model-building methodology, was fundamental for bridging the gap between theoretical modelling and practical application, further reinforcing the value of incorporating stakeholder knowledge into the analytical process. Whenever possible, such validation should be actively pursued, as it adds a layer of credibility and precision that cannot be achieved through literature review alone.

1	DOCUMENTATION REVIEW	Company's reports, technical papers, and stakeholders' commentary
2	IMPACTS IDENTIFICATION	Third-level sustainability impacts
3	TECHNOLOGICAL ENABLERS IDENTIFICATION	Digital tools making possible the project's fulfilment
4	KPIs SPECIFICATION	Quantitative mterics for each impact, from company's reports or external sources
5	INDIVIDUAL PATHWAYS CONSTRUCTION	Causal mechanisms leading from technologies to single ESG impacts
6	CLASSIFICATION & STANDARDIZATION	Digital Levers vs Operational Outputs
7	DRAFTING OF MACRO-DIAGRAMS	Separated visual maps for each of the three ESG dimensions
8	VERTICAL LAYERING	Seven-layered structure distinguishing variables basing on their nature
9	CAUSALITY REPRESENTATION	Unidirectional arrows connecting impacts and outputs with their determinants
10	SPECIFICATION OF IMPACTS DIRECTIONALITY	Increase or reduction of variables' value & improvement or worsening of performance
11	ADDITION OF DESCRIPTIONS	Textual description of each cycle's path and relationships
12	IMPACTS CLASSIFICATION	Potential vs Certain [Direct or Indirect] – Core Targets vs Unintentional Effects
13	VALIDATION	Meetings with project stakeholders and responsables

Figure 23: Methodology Creation Process

7 Model's Application to the SWM Case

7.1. Introduction

Once described how the model is effectively articulated, this chapter illustrates its structure and internal logic through the direct application to the *Smart Water Management* project and the way the introduced digital transformation contributes to sustainability outcomes. As already mentioned in the previous passage, the model was not built upon a predefined template, but gradually shaped through an iterative process that responded to the specific characteristics of the use case, balancing methodological coherence with empirical relevance.

The chapter is divided into two broad parts. The first focuses on the core components that underpin all sustainability pathways: the technologies deployed, the digital capabilities they enable, and the operational variables that translate those capabilities into organizational behaviour. These foundational tiers are not dimension-specific and appear throughout the model, often shaping multiple causal routes simultaneously.

The second part explores the model's articulation into the three ESG dimensions—environmental, social, and governance—each examined through the lens of selected KPIs, with a reconstruction of their respective causal paths and the integration of those paths into a broader visual structure.

7.2. Overview of Cross-Cutting Variables

The following section presents the foundational layers of the model, those variables that act as common drivers across all sustainability dimensions. Organized into three tiers, they reflect the progression from technological input to operational transformation, serving as the starting point of every causal path. Their recurring presence across environmental, social, and governance contexts highlights how the same digital components and their immediate effects can generate multiple repercussions, influencing diverse areas of sustainability simultaneously.

7.2.1. First-Tier Technologies

The first layer of the model includes the set of digital technologies concretely implemented within the *Smart Water Management* solution, the components which constitute the operational backbone of the project and represent the entry point for all causal chains subsequently developed. Their inclusion was guided not by abstract potential but by verified presence within the system architecture, as documented in technical specifications and documented sources related to the project.

- **IoT Sensors:** Positioned throughout the water infrastructure, IoT sensors serve as the system's primary data acquisition layer, as they enable continuous monitoring of physical parameters such as flow rate, pressure, and leakage anomalies. It is exactly this real-time data stream to constitute the raw material on which all downstream functionalities rely, obviously highlighting the fundamental role of these sensors in guaranteeing the project success. Their presence ensures early detection of critical events, enhances visibility over dispersed assets, and lays the groundwork for predictive intervention logic, making them indispensable across all three ESG areas.
- **Digital Twin:** Functioning as a dynamic, real-time replica of the physical infrastructure, this tool enables simulations, predictive modelling, and spatial visualization of the system's status. In the project, the digital twin is used to pre-localize losses, analyse what-if scenarios, and support proactive planning. Its capacity to simulate behaviours before they occur links it directly to forecasting mechanisms, which in turn influence both environmental performance and operational governance.
- **Decision Support System (DSS):** Embedded in the solution to consolidate data from the field and translate it into actionable recommendations, the DSS is designed to prioritize interventions, optimize resource allocation, and guide operational responses based on evidence. It plays a bridging role between raw data and organizational action, enhancing both the speed and quality of decisions and representing a key contributor to governance outcomes and risk mitigation.
- **Workforce Management (WFM) System:** Included in the platform to support the planning and coordination of field activities, the system enables remote task assignment, progress tracking, and digital reporting from technicians operating on-site. In the specific Smart Water Management case, it allows for improved alignment between system alerts (e.g., detected leakages) and technical responses, streamlining logistics and reducing inefficiencies.
- **Cloud Platform:** As increasingly common in today's corporate practices, all data streams and digital tools operate through a centralized cloud environment that enables integration, scalability, and multi-user access. In the project context, the cloud platform supports interoperability among systems and

ensures that information is accessible in real time by both control centres and mobile teams. This backbone supports not only data processing and storage but also cross-platform coordination, enabling integrated decision-making and reinforcing transparency across all ESG dimensions.

- **Business Intelligence (BI):** Providing dashboards and visualization tools that aggregate key indicators and performance metrics, the BI component enables operators to monitor system behaviour, detect deviations, and analyse historical trends. Within the project, BI is used to inform both operational adjustments and sustainability reporting, making it a central link between technical outputs and accountability processes.

7.2.2. Second-Tier Digital Levers

This layer of the model includes the key digital functionalities that emerge immediately from the interaction of first-tier technologies and which can be easily seen as the fundamental reasons why technologies themselves get installed. These are not yet impacts in themselves, but rather capabilities, intelligent mechanisms that translate raw digital input into operational leverage. As such, they serve as the first true inflection point in the transformation process, and are central to unlocking ESG performance improvements further along the causal chain.

Identified based on their recurrence in both the case documentation and the scientific literature as fundamental digital outputs in smart infrastructure contexts, they reflect direct functionalities observed in the project and are fully grounded in both practice and theory.

- **Forecasting accuracy:** This lever captures the system's ability to anticipate future events, such as leakages, consumption spikes, or infrastructure failures, based on historical and real-time data. In the Smart Water Management project, this functionality is activated by the integration of sensor-derived data streams and the analytical capabilities of the DSS platform, as sensors provide the dense, continuous data needed to detect trends and anomalies, while the system translates these patterns into predictive insights for operators. The selection of this variable is supported by extensive literature: on one side, Sayed et al. demonstrate how DSS platforms are central in developing forecasting intelligence, particularly when used in high-variability technical systems [167]; on the other, Mary et al. highlight the critical role of IoT-enabled data flows in improving forecasting reliability, especially when paired with scalable analytics frameworks [170].
- **Real-time monitoring:** Defined as the system's continuous awareness of its own state, which enables immediate detection of anomalies and status changes, it is not a derived insight, but a direct digital output of the IoT infrastructure

embedded across the water network. Within the case study, sensors installed at strategic points allow operators to remotely observe parameters such as flow rate, pressure, and leakage indicators, creating a responsive and transparent control environment. Its centrality in IoT-based infrastructure has been widely validated in the literature [171], which highlights its capacity to transform static utilities into live, intelligent systems.

- **Preventive maintenance:** This lever represents the system's ability to anticipate and address infrastructure issues before they result in failures or service disruptions. Unlike operational variables that reflect measurable outcomes, preventive maintenance is understood here as a digitally enabled capability, an evolved maintenance paradigm made possible by the integration of advanced technologies. In the context of the Smart Water Management project, this functionality arises from the combined action of the digital twin, the decision support system (DSS), and the workforce management (WFM) platform, which together enable a shift from reactive responses to proactive planning. As emphasized by Liu et al., the digital twin creates a real-time virtual replica of the network and consequently enables simulations of stress scenarios and predictive diagnostics essential for condition-based maintenance [175]. The DSS builds on this by transforming those simulated and real-time inputs into prioritized intervention strategies and optimized scheduling routines, a role highlighted by Obura et al., who describe the growing application of such systems in converting traditional maintenance practices into sustainable, forward-looking models [168]. Finally, the WFM system ensures the operational deployment of this intelligence by coordinating field resources and executing planned interventions, an integration that, as Akl et al. demonstrate, enhances workforce efficiency and reduces service downtime through simulation-optimization approaches [174]. The interaction of these technologies results in a proactive and resilient maintenance model with clear implications across all ESG dimensions, particularly in terms of system efficiency, risk mitigation, and long-term asset sustainability.

7.2.3. Third-Tier Operational Outputs

The third tier of the model comprises those tangible and observable changes in system behaviour that result from the activation of digital levers.

These variables represent the first measurable outcomes within the causal framework and form the bridge between technological enablement and ESG performance. Unlike digital levers, which denote abstract capabilities, third-tier variables capture practical shifts in how the system functions, making them particularly relevant for performance monitoring and indicator design.

- **Number of emergency interventions:** This variable captures the frequency of unplanned and urgent corrective actions performed on the network due to leaks, failures, or other anomalies. In the context of the project, it is expected to decrease as a direct consequence of enhanced forecasting accuracy and the implementation of preventive maintenance strategies, which allow to anticipate potential disruptions and address them proactively. The downward trend in this metric, marked by a green arrow in the model, is a clear operational manifestation of upstream digital intelligence and reflects in improved service stability and reduced resource stress.
- **Digital connectivity and complexity:** Defined as the level of interconnection, interdependence, and structural sophistication introduced by the deployment of multiple digital technologies within the system, this variable reflects a system-wide condition shaped by the infrastructure's evolving configuration. In the Smart Water Management project, this complexity arises primarily from the direct deployment of first-tier technologies, particularly the widespread installation of IoT sensors and the use of a centralized cloud platform, which represent foundational elements transforming the way data flows, systems communicate, and operations are orchestrated. Their influence does not pass through intermediate levers like forecasting or monitoring but affects the structure of the system directly, increasing the volume, speed, and variety of information exchanged, and requiring robust interoperability across hardware and software layers. As increasingly common in today's corporate practices, such integration introduces important benefits in terms of scalability and visibility, but it also generates additional complexity in managing infrastructure, securing data, and maintaining system coherence. These tensions are widely acknowledged in the literature: Gankotiya et al. discuss the inherent trade-offs in cloud-IoT integration, citing complexity as both a technical and organizational concern [172], while Ambika and Nwafor highlight the operational risks and architectural demands that such integration imposes [173]. The upward trend in this variable, represented by a red arrow in the model, reflects exactly this double-edged evolution, highlighting the need for governance structures capable of keeping pace with technological sophistication.
- **Response time to emergencies:** Measuring the time elapsed between the detection of a critical event and the execution of the corresponding intervention, it is expected to decrease as a direct result of real-time monitoring, which provides operators with continuous awareness of network conditions and immediate visibility into anomalies. In the project, this capability significantly accelerates the diagnostic and reaction phases, reducing both human delay and logistical inefficiencies. This downward trend reflects a concrete operational improvement with implications across ESG domains, from reducing water

waste and environmental risk to enhancing customer satisfaction and service accountability.

7.3. Environmental Sustainability

The environmental dimension of the model addresses how the *Smart Water Management* project affects sustainability from an ecological standpoint, with particular emphasis on aspects such as resource efficiency and emissions reduction. Given the nature of the digital transformation involved, this is the area where the strongest and most immediate repercussions are observed.

7.3.1. KPIs and Dimensions Selection

Reading the project documentation, and considering technological characteristics whose effects on environmental sustainability are highly debated in academic literature, two main second-level dimensions were selected for analysis: climate change and resources management. Then, given the nature of the implemented digital solution, each dimension was further narrowed down to only a single third-level category, respectively GHG Emissions for Climate Change, and Resource Utilization for Resources Management.

- **GHG Emissions:** The focus on GHG emissions as a third-level environmental dimension stems from the growing attention to the environmental footprint of digital infrastructure, particularly in light of recent debates on the climate implications of increasing connectivity, energy consumption and smart technologies. Although the Smart Water Management project is not explicitly designed to target emission reductions, several of its technical and operational features have measurable consequences on CO₂ outputs, both directly and indirectly. As such, this dimension allows the model to capture collateral environmental effects, offering a more nuanced perspective on how digital transformation in utilities intersects with broader climate objectives.
 - **CO2 Scope 1 Emissions (Company Vehicles):** This KPI measures direct greenhouse gas emissions produced by company-owned vehicles, typically resulting from fuel combustion during operational activities such as emergency interventions or routine maintenance. In the context of the Smart Water Management project, emissions in this category are expected to decrease due to the implementation of forecasting capabilities and preventive maintenance protocols. Indeed, as Su et al. demonstrate, predictive maintenance in asset-intensive sectors leads to significant emission reductions due to fewer site visits and vehicle

deployments, supporting the relevance of this linkage in analogous utility contexts [177].

The formula used for this KPI is drawn from the American Public Transportation Association [178], which defines Scope 1 emissions from company fleets based on activity data (e.g., distance travelled) and corresponding emission factors.

$$\text{CO}_2\text{-Scope}_1 = \sum_{i=1}^n (D_i \cdot EF_j)$$

In this model, the impact is classified as certain, as the relationship between reduced interventions and reduced travel is both intuitive and supported by empirical literature, and indirect, as the digital system does not target emissions explicitly but rather modifies operational behaviours that in turn influence emission levels through a reduction of distance travelled. Moreover, far from being a core objective of the solution, it is considered a collateral effect, meaning it is a positive externality resulting from improved efficiency.

- **CO₂ Scope 2 Emissions (Digital Infrastructure):** This KPI captures indirect emissions associated with the electricity consumption of the project's digital systems, specifically sensors, cloud platforms, decision support tools, and communication networks. The deployment of such infrastructure, in fact, increases the system's overall energy demand, particularly through continuous data processing, storage, and transmission, and in a climate impact of varying magnitude depending on the carbon intensity of the electricity supply. As Zhao points out, in fact, the environmental impact of soft and hard digital infrastructure is highly context-dependent: when powered by renewable energy or carbon-neutral data centres, emissions associated with digital operations may remain minimal, whereas reliance on fossil fuels can lead to a significantly higher carbon footprint [179]. Similarly, Belkhir and Elmeligi provide projections on ICT-related emissions, emphasizing the long-term significance of digital systems as contributors to global GHG outputs [180].

The formula adopted for this KPI is sourced from Belkhir and Elmeligi [180], which calculates Scope 2 emissions by multiplying energy consumed by emission factors specific to the energy source.

$$\text{CO}_2\text{-Scope}_2 = \sum_{i=1}^n (KWh_i \cdot EF_i)$$

For all the previously explained reasons, the impact is classified as potential, because the causal chain between digital deployment and emissions is conditional on the energy mix, which varies by context and over time. fundamentally, while the system directly increases energy use,

the emission outcome is not guaranteed. As such, this KPI is also considered a collateral effect, since emissions are not a target of the intervention but a possible byproduct of increased technological sophistication.

- **Resource Utilization:** The emphasis on resource utilization reflects the central role of the Smart Water Management project in optimizing the efficiency of physical infrastructure, reducing waste, and enabling more sustainable use of water, energy, and materials. Unlike emissions, where the impact is often collateral, this dimension includes several areas that represent core targets of the intervention and reasons why of its implementation. The selected KPIs cover three categories of resource use—water, energy, and materials—each of which is directly influenced by the technologies and digital levers implemented in the system.

- **Percentage Leakage Index (PLI):** This KPI measures the percentage of water lost in the distribution network due to leaks, bursts, or undetected faults, and therefore quantifies inefficiencies due to physical leakages, pipe bursts, or undetected failures. In the Smart Water Management project, this indicator is expected to improve significantly thanks to the deployment of IoT sensors, which enable real-time monitoring, support early leak detection, and form the foundation for intervention on anomalies before they escalate. As emphasized Ramos et al., in fact, the use of these technologies enables utilities to detect and address leaks early, thereby minimizing waste and conserving resources [181].

The formula for the Percentage Leakage Index follows the structure defined by Mazzolani et al. [182], which is calculated as the ratio between non-revenue water and total system input and therefore provides a standardized metric for comparing water losses across regions and over time.

$$PLI = \frac{V_{input} - V_{distributed}}{V_{input}}$$

Given that the technologies have been explicitly designed and deployed for the purpose of leak detection and pressure management, the impact on this KPI is classified as certain. Moreover, since the causal path does not pass through intermediate levers but results immediately from sensor-driven diagnostics, it is undoubtedly classifiable as a direct one. Finally, supported by Almagiva's documentation and disclosures, which define water losses reduction as one of the primary objectives of Smart Water Management's technical architecture, the associated impact is classified a core target.

- **Pipeline Efficiency Index (PEI):** This KPI assesses the hydraulic performance of the water distribution network by measuring the degree

to which water is transported under optimal pressure and flow conditions, without excessive energy consumption or internal losses. It captures systemic inefficiencies linked to pressure imbalances, friction losses, and suboptimal maintenance practices and, in the context of the Smart Water Management project, is expected to improve through the combined effect of preventive maintenance and flow optimization. Digital twin and DSS provide real-time visibility of the network's operating conditions, simulate flow behaviours, and allow for precise scheduling of interventions that reduce inefficiencies and stabilize system dynamics. As a consequence, such capabilities enhance pipeline performance by allowing operators to detect, predict, and correct anomalies before they impact service reliability [183].

The methodological approach for this KPI follows the formulation adopted by Karki and Rao [183], which relies on flow and pressure consistency as proxies for pipeline efficiency, and provides a robust analytical basis for evaluating infrastructure performance improvements over time.

$$PEI = \frac{V_{\text{distributed}}}{V_{\text{input}}}$$

Given that the technologies deployed act directly on the key variables that influence this index, such as flow balance, pressure regulation, and pipe wear, the impact is classified as certain. It is also considered direct, since there is no need for intermediate digital levers to mediate the effect between the technology and the performance outcome. Lastly, and similarly to the previous case, the improvement of pipeline efficiency is explicitly described in Almagro's materials as a strategic outcome of the Smart Water Management initiative, qualifying this impact as a core target.

- **Energy Consumption (TEC):** This KPI captures the total amount of energy consumed by the network management system, particularly focusing on the electricity needed to support the digital infrastructure introduced by the project. In the case of Smart Water Management, the deployment of real-time connectivity, cloud platforms, and IoT sensors inevitably introduces a baseline increase in energy demand but, as in the case of GHG emissions, the extent of that increase and its long-term environmental significance depends heavily on how the system is designed and managed. As Zhao points out, although digital systems generally consume more energy, the actual impact varies based on the use of energy-efficient protocols, low-power devices, and smart data management strategies such as edge computing and adaptive transmission [179].

This KPI is calculated following the general approach outlined in the EFRAG – E1 environmental reporting standard [184], which aggregates energy consumption data across all relevant components and activities of the system.

$$\text{TEC} = \sum_{i=1}^n (P_i \cdot h_i)$$

Although a direct consequence resulting structurally from how the infrastructure is built and operated without requiring behavioural or secondary mechanisms, the impact on this KPI is classified as potential, because the actual variation in energy demand depends on contextual and design-specific factors, such as the efficiency of devices, system architecture, and energy management protocols. Nonetheless, because energy consumption is not a primary focus of the intervention, but a monitored side effect of technological modernization, the impact is treated as a collateral effect.

- **Total Material Consumption (TMC):** This KPI reflects the quantity and typology of materials introduced into the system as a consequence of digital transformation, capturing both the materials required for the deployment of digital infrastructure (such as sensors, wiring, communication hardware, and structural components) and the materials typically consumed during operational interventions, especially emergency maintenance. In the Smart Water Management project, the former component is expected to increase, as the physical implementation of IoT and connectivity devices introduces new material demands—an effect that, as noted by Contini et al., is inherent to digitalization processes, particularly in sectors reliant on embedded hardware [185]. In contrast, the second component—materials consumed during field interventions—is expected to decrease due to the significant reduction in emergency maintenance made possible by forecasting accuracy and preventive strategies. While the net balance between these two opposing trends may vary depending on system design and maintenance cycles, the existence of a measurable transformation in material flows remains unquestionable. While no singular industry-wide formula is universally applied to this KPI, it is typically derived through material accounting practices, summing up quantities and weights of components installed, replaced, or decommissioned over the lifecycle of the project. In this specific case, to better distinguish the two described aspects, two distinct summatory components are included.

$$\text{TMC} = \sum_{i=1}^n M_i^{\text{tech}} + \sum_{j=1}^m M_j^{\text{maintenance}}$$

Given that material deployment is a necessary and quantifiable aspect of the technological rollout, the impact on this KPI is classified as certain and direct, as the materials are not introduced through user behaviour or secondary processes but as a consequence of the physical infrastructure itself. However, material consumption is not an objective of the project—whether to increase or reduce it—justifying therefore the classification under the category of collateral effect.

7.3.2. Individual Causal Paths

The following section details the specific causal mechanisms through which the Smart Water Management system influences the selected environmental KPIs. Each path is reconstructed by tracing the flow from enabling technologies to intermediate capabilities and operational shifts, ultimately highlighting how digital interventions produce measurable impacts on ecological performance indicators.

- **CO₂ Scope 1 Emissions (CO₂-FI):** Deployed across the network to collect high-frequency data on flow, pressure, and asset behaviour, IoT sensors transmit information streams directly to the Decision Support System, which through trained algorithms and historical analysis, generates predictive insights that enhance forecasting accuracy. This predictive layer allows early identification of anomalies and deteriorating conditions, laying the foundation for proactive responses.

Simultaneously, the Digital Twin offers a dynamic virtual model of the water infrastructure, enabling simulations of asset performance under various stress conditions and supporting the detection of early signs of failure or inefficiency. When integrated with the DSS and the Workforce Management System (WFM), the system enables optimized scheduling and execution of preventive maintenance, reducing the need for urgent and unplanned interventions.

Together, forecasting accuracy and preventive maintenance significantly lower the number of emergency interventions, shifting the system from reactive repair toward anticipatory management. This change obviously has direct implications for logistics: fewer emergencies reduce the distance travelled by maintenance vehicles and lower overall fuel consumption and, as a result, CO₂ emissions from company vehicles (Scope 1) decrease, producing a measurable improvement in the project's environmental footprint.

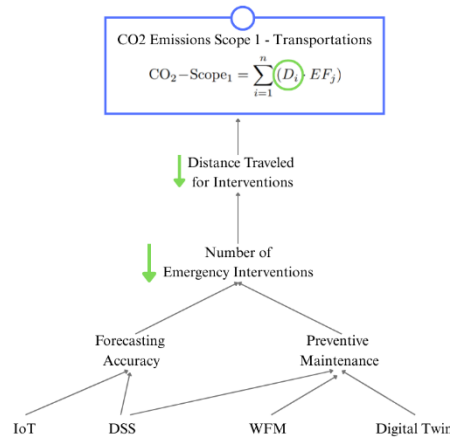


Figure 24: CO₂ Scope 1 Emissions (CO₂ -FI) Individual Cycle Path

- CO₂ Scope 2 Emissions (CO₂-DI):** Continuously transmitting high-frequency data from the field, IoT sensors are central to the real-time monitoring functionality of the Smart Water Management system. These data flows are sustained and orchestrated through a robust Cloud Infrastructure, which provides centralized processing power, remote access, and cross-platform interoperability. Together, these technologies establish a digitally connected ecosystem characterized by high levels of system integration, continuous communication, and advanced control capabilities.

This interconnected infrastructure, while essential for operational efficiency, demands a continuous supply of electricity to power edge devices, processing units, and cloud servers. As digital connectivity and system complexity increase, so too does the overall energy consumption of the system, especially in its digital components. This rising energy demand potentially translates into a corresponding increase in CO₂ emissions from electricity use (Scope 2), particularly when the underlying energy supply is dependent on fossil fuels.

As already mentioned, however, the resulting impact on the KPI is tied not only to the technological architecture itself but also to the carbon intensity of the electricity mix, making the emission outcome a context-dependent consequence of an otherwise essential digital transformation.

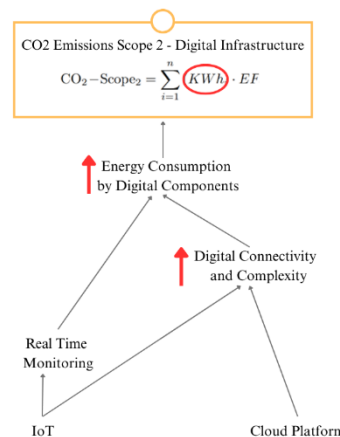


Figure 25: CO₂ Scope 2 Emissions (CO₂-DI) Individual Cycle Path

- Percentage Leakage Index (PLI) and Pipeline Efficiency Index (PEI):**
 Strategically distributed throughout the network, IoT sensors generate a constant stream of real-time data related to system conditions such as pressure variations, flow rates, and hydraulic anomalies. This data is continuously processed by the Decision Support System, which applies predictive algorithms to detect deviation patterns and forecast potential failures. In this way, forecasting accuracy is significantly enhanced, allowing maintenance teams to act before incidents materialize.

At the same time, the presence of real-time monitoring capabilities ensures that when anomalies do occur, they are identified and localized immediately. Together, these two digital levers, forecasting accuracy and real-time monitoring, not only reduce the number of emergency interventions, but also minimize response time by enabling faster, more targeted reactions.

As a result, leaks are detected earlier and addressed more effectively, leading to a tangible drop in water losses across the system. This leads to a simultaneous improvement of both the Percentage Leakage Index (PLI) and the Pipeline Efficiency Index (PEI), as consistent flow is promoted, pressure imbalances reduced, and inefficiencies that typically degrade network performance eliminated.

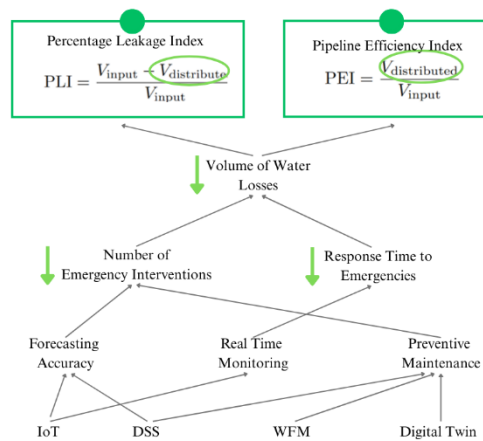


Figure 26: Percentage Leakage Index (PLI) and Pipeline Efficiency Index (PEI) Individual Cycle Path

- Technological Energy Consumption (TEC):** The always-on nature of the Smart Water Management system, driven by the uninterrupted operation of IoT sensors deployed across the water network, creates a continuous baseline of energy demand. Indeed, exactly to support real-time monitoring and data transmission, these sensors must operate 24/7 and are further sustained by cloud-based servers that manage data aggregation, storage, and distribution. As the scale of this infrastructure grows, so too does its structural complexity and degree of digital interconnection and the Cloud Infrastructure, although playing a pivotal role in maintaining interoperability between platforms and ensuring high system responsiveness, amplifies the system's energy requirements, especially in high-throughput conditions. Together, the expansion of digital components and the rise in system-level integration result in a steady increase in Technological Energy Consumption (TEC). This trend reflects an unintended but direct consequence of digitalization, reinforcing the importance of energy-efficient configurations and renewable energy sourcing to mitigate its environmental burden.

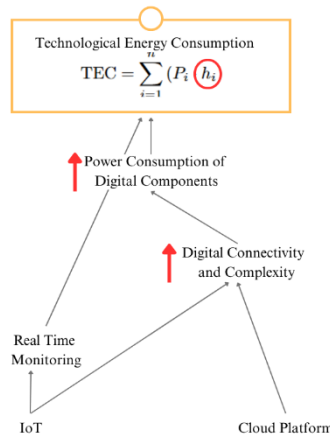


Figure 27: Technological Energy Consumption (TEC) Individual Cycle Path

- **Total Material Consumption (TMC):** The physical implementation of the Smart Water Management system involves the deployment of a wide array of IoT sensors, communication devices, and cloud-supporting infrastructure across the water network, whose creation process obviously require a considerable volume of materials such as metals, plastics, cables, and mounting hardware.

In parallel, however, the integration of the Digital Twin, DSS, and Workforce Management System enables a proactive maintenance regime based on predictive insights and optimized scheduling, which allows to decrease the need for unexpected field restorations. By anticipating asset failures and coordinating interventions, in fact, the system significantly reduces the frequency and urgency of emergency repairs, which are typically more resource-intensive and involve higher consumption of tools, spare parts, and temporary materials.

This dual dynamic creates a bidirectional effect on the Total Material Consumption (TMC) KPI: while material use increases due to the deployment of digital infrastructure, it simultaneously decreases as emergency maintenance becomes less frequent and more targeted. The final impact on the KPI depends on the relative weight of these two trends, making material consumption a highly implementation-sensitive dimension of environmental sustainability.

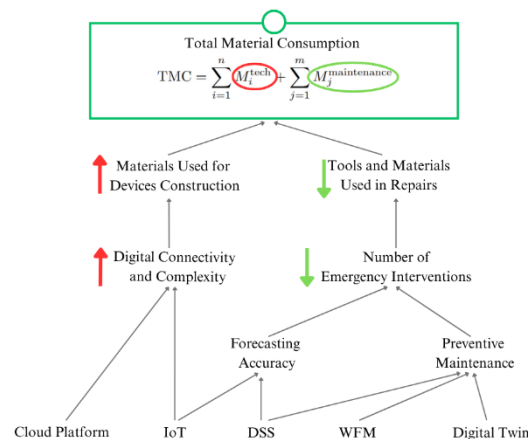


Figure 28: Total Material Consumption (TMC) Individual Cycle Path

7.3.3. Comprehensive Map

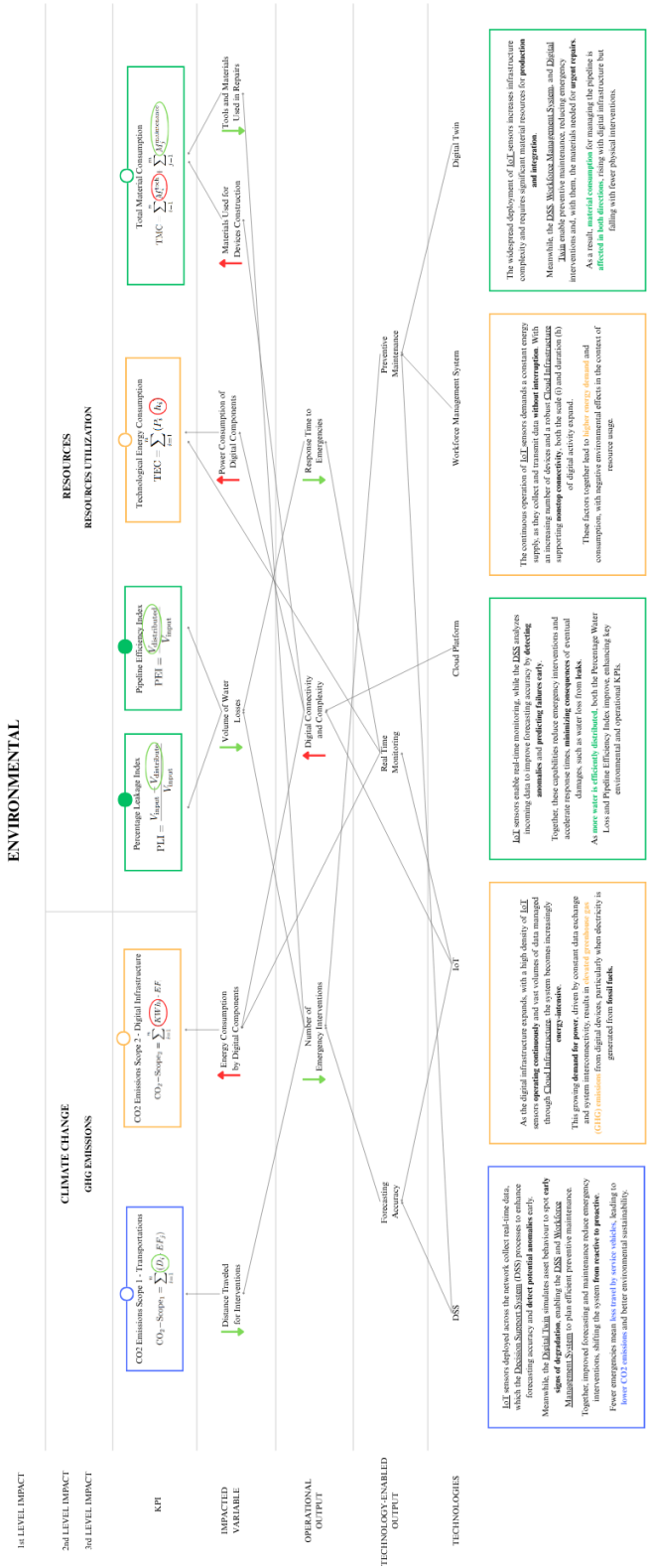


Figure 29: Comprehensive Environmental Map

7.4. Social Sustainability

The social dimension of the model explores how the Smart Water Management project influences human-centred aspects of sustainability, such as equity in service access, occupational safety, and digital responsibility. Unlike environmental KPIs, where impacts were often structural or systemic, social KPIs reflect how technological transformations reshape working conditions, user experiences, and organizational practices. In this sense, the social impacts of the project are both operational and societal, encompassing benefits like improved access to clean water, enhanced training for staff, and increased safety in the field.

7.4.1. KPIs and Dimensions Selection

Based on project documentation and literature emphasizing the human and organizational implications of digital transformation, four second-level social dimensions were selected as most relevant to the project: access to resources, education, work and income, and security. Each of these was then narrowed down to one or maximum two third-level categories, sharpening even more the desired target.

The resulting focus areas reflect a combination of direct system functionalities and broader structural implications introduced by digitalization, interestingly highlighting how a project originally thought for environmental purposes can actually have significant repercussions also within the social landscape.

- **Access to Services:** The focus on this third-level social dimension stems from the recognition that infrastructure reliability and service continuity are essential prerequisites for equitable and inclusive development. While this category broadly includes services such as energy, healthcare, transportation, finance, and legal support, in the context of Smart Water Management the emphasis is specifically on water supply as a public utility. Although the project does not expand geographic coverage or build new physical networks, it significantly enhances service availability by minimizing system downtime and improving operational responsiveness. As such, this dimension captures one of the most tangible social benefits of the intervention: ensuring that existing services remain consistently accessible, particularly in urban and semi-urban environments where interruptions can have immediate impacts on well-being.
 - **Water Source Availability (WSA):** This KPI measures the reliability of water availability for end users, typically expressed as the percentage of time a functional water source is accessible within a given area. Although the Smart Water Management system does not act directly on water sources, it has a significant indirect impact on their availability as, through the combined deployment of DSS and digital twin technologies, the system enables early detection of failures and predictive maintenance,

reducing the occurrence and duration of unplanned outages. As Ramos et al. note, these technologies enhance the efficiency and resilience of water distribution networks, ultimately increasing uptime and service stability [181].

The formula used to define this KPI is adopted from Dasallas et al. [186], where it is calculated as one minus the ratio of downtime over total time observed.

$$WSA = 1 - \frac{T_{\text{down}}}{T_{\text{total}}}$$

Given the close relationship between system reliability and service continuity, the impact on this KPI is classified as certain and indirect: the technologies do not intervene on the service directly, but through upstream reliability improvements and better operational management. Nevertheless, because the enhancement of water availability is a fundamental performance objective of the project, the effect is considered a core target of the intervention.

- **Professional Training:** This third-level dimension refers to the accessibility and quality of vocational and technical education, with particular emphasis on cost, availability, and the alignment between training programs and labour market demands. In the case of Smart Water Management, digital transformation introduces new layers of system complexity and reshapes the skill sets required of operational personnel, making necessary the development of technical competencies related to data interpretation, troubleshooting, and digital system management. This dimension therefore captures the organizational adaptation required to keep pace with innovation and reflects how technological evolution influences workforce development in practice.
 - **Technical Training Rate (TTR):** This KPI captures the proportion of employees who have undergone technical training relative to the total workforce, reflecting the systemic shift in skill requirements caused by the integration of IoT, cloud platforms, and DSS tools. In the Smart Water Management project, the introduction of these digital systems creates an immediate operational need for staff capable of managing, interpreting, and troubleshooting the new technologies. As Kuznetsova and Neboha explain, digital modernization directly increases the need for professional education in technical domains, particularly in complex systems like smart water grids [187].

The calculation of this KPI follows the model proposed by Contini et al. [185], defined as the total hours of technical training delivered divided by the total number of employees.

$$TTR = \frac{\text{Hours Technical Training}}{\text{Total Employees}}$$

Given that training requirements arise immediately and structurally from the technologies introduced, the impact on this KPI is considered certain and direct. However, because raising the training rate is not a primary design objective of the project but an operational necessity that emerges alongside technological change, the effect is classified as a collateral impact.

- **Work Standards:** Focusing on themes such as fair compensation, work-life balance, employee satisfaction, occupational safety, and the elimination of child labor, this third-level category generally addresses the quality and safety of working conditions. Within the scope of project, the most relevant aspect is related to the physical risks faced by field technicians as the shift from reactive emergency interventions to planned, predictive maintenance significantly reduces exposure to hazardous conditions. This dimension thus reflects the project's indirect but important contribution to improving workplace safety by structurally altering how and when work is performed.
 - **Rate of Recordable Work-Related Injuries (RWRWI):** This KPI measures the frequency of workplace injuries per hours worked and reflects the overall safety conditions experienced by operational personnel. In the Smart Water Management project, this indicator is particularly relevant due to the shift from reactive to preventive maintenance strategies made possible by technologies such as DSS and forecasting tools. The latter, in fact, reduce the number of emergency field interventions, which are typically associated with higher safety risks such as exposure to hazardous environments, working at night, or responding to high-pressure failures. As explained by Assilzadeh and Gao, integrating predictive maintenance and real-time monitoring significantly improves technician safety by allowing interventions to occur under more controlled and less urgent conditions [188].

The formula used, which is already implemented by Almagiva itself, is drawn from the Global Reporting Initiative [189], where the rate is calculated as the number of recordable work-related injuries per total hours worked.

$$RWRI = \frac{\text{Recordable Work Related Injuries}}{\text{Hours Worked}}$$

Although the technologies involved do not act directly on safety protocols or equipment, the systemic change they enable (i.e., minimizing exposure to hazardous scenarios) has a certain impact on this KPI. The causal link is classified as indirect, since the reduction in injuries results from altered work conditions rather than from a direct intervention on safety. Nonetheless, because protecting worker well-being is a recognized

outcome of the predictive strategy adopted, the effect is considered a core target of the Smart Water Management solution.

- **Food Safety:** The dimension refers to the protection of public health through the assurance of hygienic, contaminant-free food and water, and includes aspects such as ingredient quality and the prevention of physical, chemical, or biological contamination. In Smart Water Management, digital twins and real-time sensors continuously monitor water quality parameters, not only ensuring that distributed water complies with safety standards before it reaches consumers but also determining broader implications on food preparation, agriculture, and public health infrastructure. In this case, the dimension captures the preventive capacity of digital tools in reducing contamination risks and supporting consistent compliance with regulatory thresholds.

- **Water Quality Compliance (WQC):** This KPI expresses the percentage of water samples that meet safety standards in terms of turbidity, contaminants, pH, and other physical or chemical properties, which obviously have repercussions on the human health. In the context of Smart Water Management, this KPI is directly influenced by real-time monitoring systems that continuously assess water quality parameters throughout the distribution network, enabling early anomaly detection and preventing potential contamination from reaching consumers. As described by Baena-Miret et al., the adoption of digital twins in water networks substantially improves both efficiency and quality control by enabling preventive and immediate responses to deviations in quality thresholds [190].

The formula for this KPI is adapted from the Urban WaSH Learning Resource [191], calculated as the proportion of compliant water samples over total samples collected.

$$WQC = 1 - \frac{\text{Samples}_{NC}}{\text{Samples}}$$

Given the continuous and automated nature of the monitoring process, the impact is certain and direct: technologies are specifically designed to measure, report, and respond to water quality issues in real time. Moreover, ensuring water safety is central to public service obligations in utility management, and the contribution of SWM to compliance rates is therefore classified as a core target of the system.

- **Cybersecurity:** The focus on this third-level category is justified by the increasing concerns about protection of data from digital systems, ensuring confidentiality, integrity, and availability while safeguarding individual rights. As utility systems become increasingly digitized, the surface area for potential cyber threats expands, introducing new risks tied to system access, data integrity, and remote monitoring. In the Smart Water Management project,

cloud-based infrastructure and IoT connectivity improve operational control but also require robust security protocols, eventually highlighting the vulnerabilities introduced by digital integration and the need to manage them through security-by-design principles, authentication controls, and real-time threat monitoring.

- **System Vulnerability (SV):** This KPI evaluates the susceptibility of the system to software vulnerabilities and cyber threats, typically increased by the rapid expansion of digital surfaces such as cloud platforms, connected sensors, and remote access tools. However, as Singh et al. argue, such risks only materialize if systems are poorly configured or if security-by-design principles are not embedded into the infrastructure from the outset [192]. The mere increase in digital complexity, which is evident in the case of SWM, does not automatically lead to greater vulnerability, but it does raise the need for deliberate mitigation strategies.

The KPI structure is inspired by the work of Agyepong et al. [193], who propose tracking discovered vulnerabilities over time as a way to assess security performance in digital operations centres.

$$SV = \frac{\text{Vulnerabilities Discovered}}{\text{Period}}$$

As already mentioned, although the possibility of increased system vulnerability exists, the realization of that risk is conditional upon design and governance choices, justifying the impact categorization as potential. The causal relationship, on the other side, is direct, as the exposure stems from the infrastructure itself and not from downstream behaviours. Finally, since the management of cybersecurity risks is not a primary focus of the SWM project but a necessary safeguard to avoid unintended harm, this KPI is categorized as a collateral effect.

- **Remote Access Control (RAC):** This KPI measures the effectiveness and security of mechanisms that govern digital entry points to the system, especially those made accessible through cloud platforms, mobile interfaces, or remote operations centres that are all essential to enable real-time monitoring and remote intervention in the context of the SWM project. As already indicated by Singh et al. [192] and further stressed by Chew et al. [194], even if the presence of risks does not imply their automatic materialization, cloud-based systems that lack adequate encryption, authentication protocols, or access controls may become vulnerable to unauthorized intrusions.

While there is no universal metric for RAC, it can be assessed through the number of unauthorized accesses through identified system entry points, as referenced in NIST's Performance Measurement Guide for Information Security [194].

$$\text{RAC} = \frac{\text{Unauthorized Accesses}}{\text{Remote Access Points}}$$

In this context, although the direct link due to the increase of access points' number irrespective of usage behaviour, the impact of the technology on the KPI is classified as potential, since the effect only manifests in cases of inadequate protection. Yet, because intrusion prevention is not an explicit objective of the system, but rather a background condition to be monitored and mitigated, the impact is considered a collateral effect.

7.4.2. Individual Causal Paths

As done for the environmental dimension, the following section reconstructs the specific causal mechanisms through which the Smart Water Management system influences each of the selected social KPIs. By tracing the paths from enabling technologies through intermediate capabilities and operational changes, it becomes possible to understand how digital transformation not only enhances technical performance but also reshapes workforce dynamics, service reliability, and public well-being.

- **Water Source Availability (WSA):** The improvement in forecasting accuracy stems from the combined deployment of IoT sensors and the Decision Support System (DSS) as, while the former provide the dense, high-frequency data streams necessary to monitor real-time system behaviour, the latter processes this information through predictive algorithms and identifies trends, anomalies, and potential points of failure before they materialize.

In parallel, the shift toward preventive maintenance is supported by the integrated use of the DSS and Workforce Management System (WFM) with the Digital Twin, which offers a continuously updated virtual replica of the network and therefore enables simulations and stress-testing of asset conditions. These insights are then used by the DSS to prioritize interventions based on risk and urgency, while the WFM system translates strategic planning into coordinated field operations.

The convergence of these two digital levers, forecasting accuracy and preventive maintenance, leads to a sustained decrease in the number of emergency interventions, which in turn reduces system downtime. The result is a measurable improvement in water source availability (WSA), as the infrastructure becomes more stable, resilient, and capable of delivering continuous service to communities.

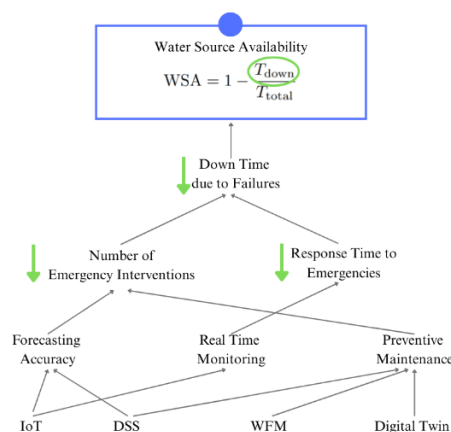


Figure 30: Water Source Availability (WSA) Individual Causal Path

- **Technical Training Rate (TTR):** The introduction of smart technologies into the water network, particularly IoT sensors and Cloud Infrastructure, creates a more sophisticated operational environment that requires employees to navigate complex data flows, real-time diagnostics, and automated control layers. These new functionalities not only demand a higher level of digital literacy and system awareness, but also transform both the nature and scope of technical roles within the organization as a consequence of increased digital connectivity and complexity. In addition, tools such as the Decision Support System further raise the bar for operational competence by introducing analytics-driven workflows that require staff to understand predictive outputs and make data-informed decisions. As the entire system becomes more reliant on intelligent digital tools, the demand for upskilling becomes structural. In response, organizations are prompted to invest in targeted training programs, leading to a visible rise in the technical training rate (TTR) that highlights how technological modernization reshapes workforce development priorities.

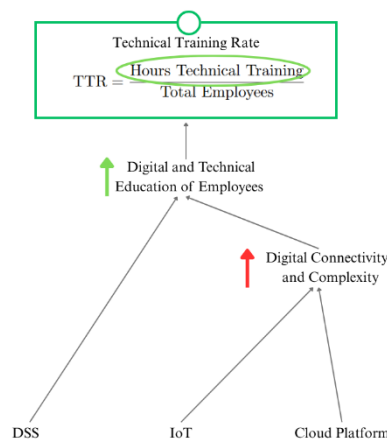


Figure 31: Technical Training Rate (TTR) Individual Causal Path

- **Rate of Recordable Work-Related Injuries (RWRI):** Deployed across the network to monitor real-time conditions such as flow anomalies, pressure variations, and equipment stress, IoT sensors supply the Decision Support System with continuous high-resolution data streams. The DSS, equipped with predictive analytics and trained algorithms, interprets this information to anticipate failures and identify emerging risks before they manifest. In parallel, the Digital Twin constructs a continuously updated virtual replica of the water infrastructure, enabling stress-testing and scenario simulations that further refine failure predictions and risk prioritization.

When combined with the Workforce Management System (WFM), these technologies form an integrated operational ecosystem that supports forecasting accuracy and enables the implementation of structured preventive maintenance.

Together, these digital levers drive a systemic reduction in emergency repairs, which are typically carried out under pressure, in unsafe environments, and without sufficient preparation, and replace them with pre-planned, lower-risk maintenance tasks. As a direct outcome, the Rate of Recordable Work-Related Injuries declines, marking a tangible improvement in occupational safety and affirming the role of digitalization as a structural enabler of workforce protection.

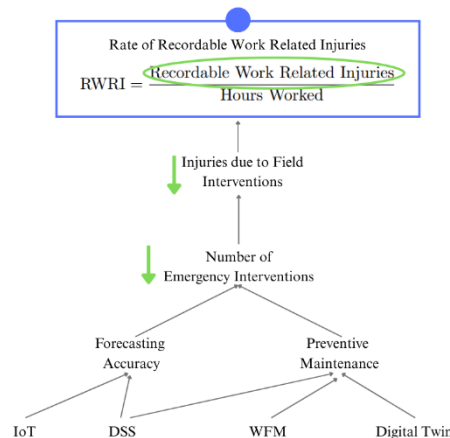


Figure 32: Rate of Recordable Work-Related Injuries (RWRI) Individual Causal Path

- **Water Quality Compliance (WQC):** The widespread deployment of IoT sensors throughout the water distribution network enables real-time monitoring of key quality parameters, such as turbidity, pH levels, and potential contaminants, and allows for the immediate detection of deviations from established safety thresholds.

At the same time, the integration of the DSS, WFM system, and Digital Twin supports a robust preventive maintenance strategy that includes anticipating

contamination risks, scheduling proactive inspections, and conducting targeted interventions before water quality deteriorates.

As a result, by combining constant surveillance with predictive operational planning, the system is able to prevent or quickly respond to emerging threats, reducing both the frequency and severity of water safety breaches. With the proportion of samples that meet established safety standards growing, the Water Quality Compliance (WQC) increases, reinforcing public health protections and enhancing service reliability across the network.

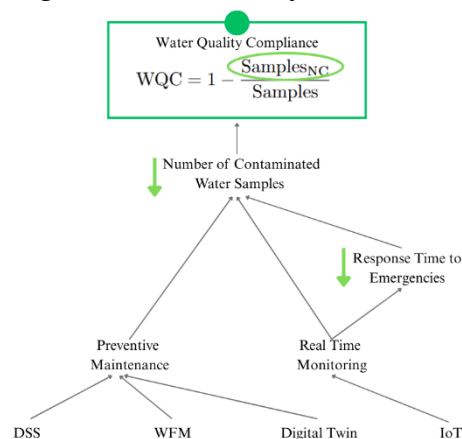


Figure 33: Water Quality Compliance (WQC) Individual Causal Path

- System Vulnerability (SV):** The deployment of IoT sensors and the expansion of Cloud Infrastructure increase the digital footprint of the water network, enabling unprecedented levels of automation, interoperability, and remote management. However, despite significantly improving operational efficiency, these advances also expand the potential attack surface through the introduction of a larger number of connected components and communication interfaces. In fact, as the digital connectivity and complexity of the system grow, so too does its exposure to cyber threats: each added sensor, data exchange, or integration layer introduces potential vulnerabilities, which, if not properly managed, could be exploited by malicious actors. This makes cybersecurity risk not only more prevalent, but more difficult to manage through traditional reactive methods.

The increase in potential attacks, whether or not they are ultimately exploited, raises the system's System Vulnerability (SV) index, ultimately highlighting the need for advanced security protocols and reinforcing the idea that digital transformation must be accompanied by equally sophisticated governance mechanisms to safeguard system integrity.

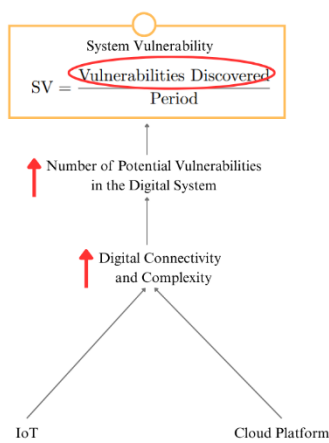


Figure 34: System Vulnerability (SV) Individual Causal Path

- **Remote Access Control (RAC):** IoT sensors and Cloud Infrastructure are fundamental to enabling real-time monitoring and decentralized control in the Smart Water Management system. However, the same capabilities that enhance visibility and responsiveness also introduce a greater number of attackable digital access points, as each connected device and integration interface represents a possible entry channel to the network that collectively expands the architecture’s accessibility layer.

As the number of entry points increases, so does the potential for unauthorized access, especially in the absence of robust identity verification, encryption, or access management policies.

Without such safeguards in place, the Remote Access Control (RAC) index may worsen, reflecting increased exposure to cyber-intrusions. Indeed, even though this risk does not manifest automatically, it remains a latent consequence of the system’s design, underscoring the need to embed cybersecurity considerations from the earliest stages of digital integration.

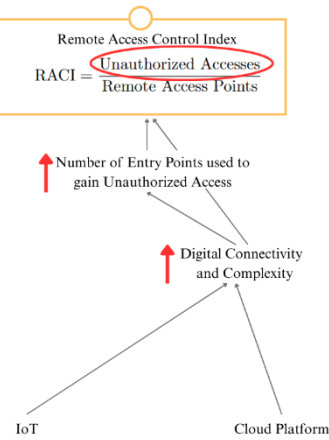


Figure 35: Remote Access Control (RAC) Individual Causal Path

7.4.3. Comprehensive Map

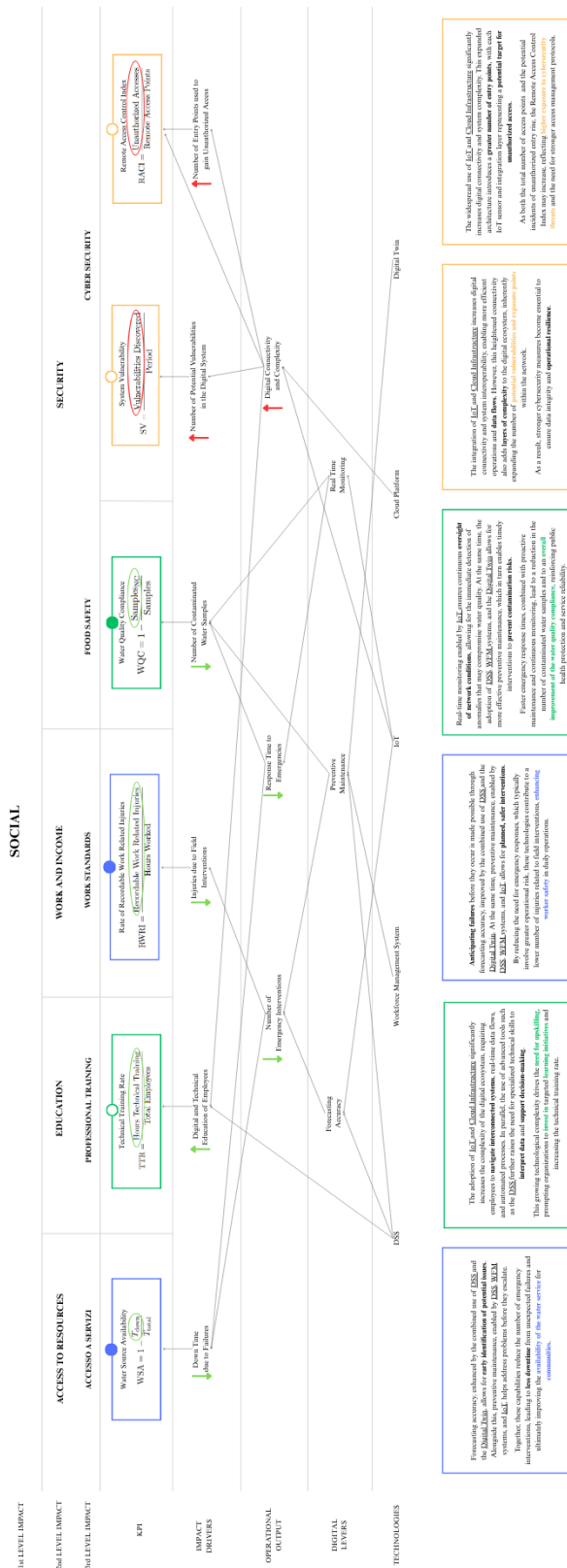


Figure 36: Comprehensive Social Map

7.5. Governance Sustainability

The governance dimension of the model focuses on how Smart Water Management improves strategic oversight, risk control, and decision-making processes within the utility. Unlike environmental or social dimensions, where outcomes are often tangible and user-facing, governance impacts emerge from improved system intelligence, monitoring capabilities, and performance transparency. These effects are particularly relevant in digitalized infrastructures, where data availability and real-time responsiveness are central to effective and accountable operations.

7.5.1. KPIs and Dimensions Selection

Based on a review of governance-related effects observed in digitally enabled utilities, and referencing to the originally developed framework, only the two second-level dimensions of communication and risk management were selected for analysis. Narrowed down to their respective third-level categories, these dimensions focus on pivotal aspects of how information is generated and shared within the organization, and how operational threats are identified, anticipated, and managed. Together, they capture the core governance implications of the Smart Water Management project, emphasizing its contribution to more transparent decision-making and more resilient infrastructure oversight.

- **Information Asymmetry:** The focus on this third-level category stems from the critical importance of equitable access to relevant, timely, and structured information within complex organizational systems. In the Smart Water Management project, the risk of information hiding and misinterpretation is mitigated through the integration of Business Intelligence tools and IoT-enabled data streams, which allow real-time operational insights to be shared transparently across different managerial levels. By ensuring that key actors have a shared understanding of system status and trends, the project contributes to improved governance, builds organizational trust, and enables faster, evidence-based decision-making.
 - **Potential Utility (PU):** This KPI assesses the proportion of information that is automatically made available to decision-makers in a structured and usable format, relative to what is actually needed for informed action. In the Smart Water Management project, this capability is primarily driven by the integration of Business Intelligence systems and IoT infrastructures, which together enable the automatic aggregation, processing, and visualization of operational data. Through digital dashboards and real-time analytics, the system ensures that critical insights, such as leak alerts, maintenance priorities, and consumption trends, but KPIs as well, are not

only available but also accessible in formats that support rapid, informed decision-making. As observed by Bettin, digital transformation in the water sector greatly enhances governance processes by increasing the relevance, clarity, and timeliness of available information, ultimately reducing the decision gap [195].

The methodological structure for measuring this KPI is based on the framework proposed by Zhuang et al. [196], where Potential Utility is calculated as the ratio of automatically displayed elements to total needed elements for decision-making.

$$PU = \frac{\text{Automatically Displayed Information}}{\text{Total Needed Information}}$$

Given the design of the Smart Water Management architecture, where Business Intelligence and sensor platforms work together to continuously present structured information, the impact on this KPI is classified as certain and direct. As a matter of fact, the generation and delivery of information is intrinsic to how the system operates, and there is no need for behavioural mediation or process adaptation for the benefits to manifest. Furthermore, because the enhancement of decision support is not a secondary outcome but a deliberate function of the technology, this KPI is considered a core target of the intervention.

- **Operational Risk:** This category includes the risks associated with day-to-day operational activities, encompassing failures in systems, human error, or inefficiencies in processes which, in critical infrastructures such as water management, can lead to service interruptions, resource waste, or even public safety concerns. The Smart Water Management project directly addresses this dimension through predictive maintenance, anomaly detection, and real-time monitoring, that together reduce the probability of system failures by anticipating them in advance and optimizing the timing of interventions.
 - **Proactive Work Ratio (PWR):** This KPI measures the proportion of total maintenance hours that are proactively planned, as opposed to being spent on reactive interventions, providing therefore insights into the degree to which a system operates under a predictive, forward-looking maintenance regime. In the project under analysis, this shift is structurally embedded into the system's logic, as the combined deployment of DSS, Digital Twin, and WFM systems enables precise diagnostics, anticipatory planning, and optimized scheduling, which together reduce emergency interventions and increase the share of scheduled, condition-based maintenance. As discussed by Mabwe, aligning maintenance activity with predictive models leads to a natural increase in planned interventions, as fewer breakdowns require urgent response [197].

The formula adopted here follows Mabwe's model [197], where PWR is calculated as the ratio of hours spent on proactive maintenance to the total of proactive and reactive maintenance hours.

$$PWR = \frac{\text{Hours}_{\text{Proactive}}}{\text{Hours}_{\text{Proactive}} + \text{Hours}_{\text{Reactive}}}$$

Because the technologies deployed are specifically designed to enable and expand proactive maintenance capabilities, the impact on this KPI is classified as certain and direct, i.e. emerging immediately from the shift in operational routines facilitated by the system. However, since increasing proactive work is not an explicit strategic goal of the Smart Water Management initiative but rather an embedded operational outcome, the effect is best understood as a collateral impact.

- **Mean Time Between Failures (MTBF):** This is a key indicator of system reliability, measuring the average time elapsed between two unexpected failures. In the context of Smart Water Management, technologies such as DSS and IoT sensors play a central role in identifying stress signals, while digital twins support simulation-based planning that allows predictive diagnostic and reduces overloading or wear. Bhanage et al. confirm that digital anomaly detection systems are highly effective in decreasing the frequency of failures, as they allow earlier and more accurate mitigation [198].

The formulation for this KPI is consistent with that proposed by Berrabah et al. [199], where MTBF is calculated as total system operating time divided by the number of unexpected failures recorded during that period.

$$MTBF = \frac{\text{Total Operating Time}}{\text{Unexpected Failures}}$$

While MTBF improves as a result of technological integration, the technologies themselves do not extend asset life directly but rather reduce strain and enable more efficient operation and planning, indirectly influencing reliability cycles. For this reason, the impact is classified as certain but indirect. Nonetheless, since reducing failure frequency is central to the goals of the system, which aims at improving service consistency and reducing inequalities in terms of access, the KPI is identified as a core target of the Smart Water Management approach.

- **Mean Time to Detect (MTTD):** This KPI captures the time required to detect a system anomaly after it has occurred, representing a critical aspect of incident responsiveness. Improvement is enabled through the constant stream of real-time data from IoT sensors embedded across the water infrastructure. These sensors automatically monitor flow, pressure, quality, and other vital indicators, issuing alerts the moment a threshold

is exceeded. Indeed, as Ren et al. show, such systems are designed to ensure minimal latency in fault recognition by removing the need for manual inspection or post-event analysis [200].

Using the definition provided by the just mentioned authors [200], the KPI is calculated using the total time taken to detect anomalies divided by the number of unexpected failures.

$$MTTD = \frac{\sum(T_{\text{Detection},i} - T_{\text{Occurrence},i})}{\text{Unexpected Failures}}$$

Because anomaly detection is an autonomous function of the installed monitoring infrastructure, and because no intermediate behavioural or procedural layer mediates the detection process, the impact on this KPI is certain and direct. Additionally, early detection is a fundamental capability that underpins many other outcomes in the system, positioning this KPI as a core target of the intervention.

- **Recall:** In the analysed context, the KPI refers to the system's ability to correctly anticipate failures thanks to the synergistic use of DSS, IoT sensors, and Digital Twin platforms, which analyse vast streams of operational data to identify risk patterns, simulate likely outcomes, and issue proactive alerts. As demonstrated by Asadi [201], systems designed around predictive logic achieve significantly higher Recall rates, thereby increasing preparedness and reducing both damage and downtime. The formula for Recall follows standard classification metrics in predictive maintenance, where it is defined as the number of correctly predicted failures (true positives) divided by the total number of actual failures.

$$\text{Recall} = \frac{\text{Issues Detected Proactively}}{\text{Unexpected Failures}}$$

Because predictive diagnostics is one of the foundational goals of the Smart Water Management system, the impact on this KPI is classified as certain, direct, and aligned with a core target of the project. The system is explicitly engineered to improve this performance dimension, making the KPI not just a byproduct but a defining measure of technological effectiveness.

7.5.2. Individual Causal Paths

This section outlines the causal chains through which the Smart Water Management system contributes to improved governance outcomes. By mapping how technological components activate specific digital capabilities and reshape operational behaviours, each path illustrates how enhanced visibility, control, and predictive planning translate into measurable improvements in oversight, reliability, and risk mitigation across the selected KPIs.

- **Potential Utility (PU):** The integration of IoT sensors across the water network enables continuous, high-frequency data collection on system performance, operating conditions, and emerging anomalies. These data flows are automatically routed into Business Intelligence (BI) systems, which structure, analyse, and translate raw inputs into performance indicators and decision-relevant insights. Dashboards generated through these BI platforms present information in a clear, accessible, and action-oriented format, ensuring that operational managers and governance actors have timely access to relevant information.

This seamless data-to-dashboard pipeline dramatically improves the Potential Utility of decision-support tools, defined by Zhuang et al. [196] as the extent to which dashboards can support their intended tasks by delivering useful, structured, and contextualized information. Advantages are evident not only in the context of internal governance, where faster and more informed decision-making is supported, but also relatedly to external audience and communication with stakeholders, as more and clearer information becomes constantly available.

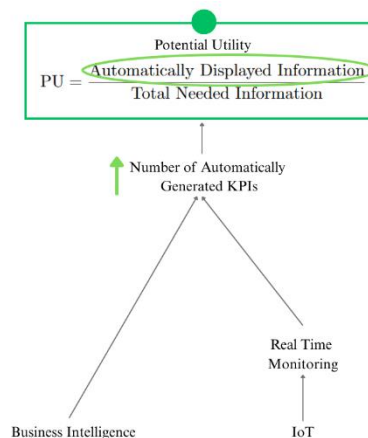


Figure 37: Potential Utility (PU) Individual Causal Path

- **Proactive Work Ratio (PWR):** The implementation of forecasting accuracy, driven by the synergy of DSS and IoT sensors, enables earlier identification of operational issues and a more informed allocation of resources. In parallel, preventive maintenance, made possible through the coordinated use of DSS, Workforce Management Systems, and the Digital Twin, allows for risk-based scheduling of interventions and optimized workforce deployment. These capabilities collectively reduce the number of emergency interventions, traditionally unpredictable and resource-intensive, while increasing the share of planned, scheduled, and data-informed maintenance actions. As a result, a larger proportion of operational time is spent on proactive rather than reactive activities, reflecting in a higher Proactive Work Ratio (PWR) that

enhances governance by demonstrating stronger control over operational planning, reduced exposure to risk, and more efficient use of personnel and infrastructure.

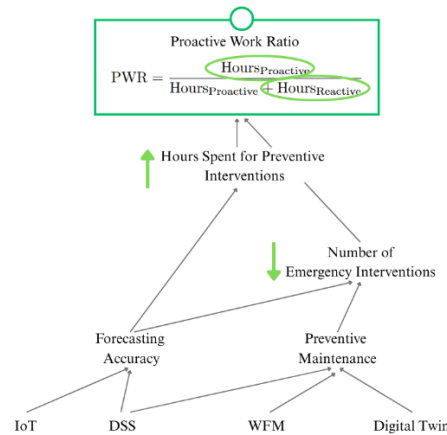


Figure 38: Proactive Work Ratio (PWR) Individual Causal Path

- Mean Time Between Failures (MTBF):** The continuous real-time monitoring enabled by a dense network of IoT sensors, which track pressure, flow, and other key parameters throughout the infrastructure, allows to detect deviations from normal operating conditions and transmit this data for immediate analysis. In parallel, the Decision Support System (DSS) processes these data streams to identify early-warning signals and simulate stress scenarios, thereby enhancing forecasting accuracy and enabling more informed risk assessment. Building on these predictive capabilities, the system deploys preventive maintenance strategies, coordinated through the DSS, Workforce Management System (WFM), and Digital Twin, to schedule timely interventions that mitigate asset degradation before it leads to failure. As a result, the frequency of emergency events declines, and the time between unplanned interruptions increases, leading to an overall tangible improvement in Mean Time Between Failures (MTBF) that reflects greater system stability, reduced operational risk, and enhanced infrastructure reliability.

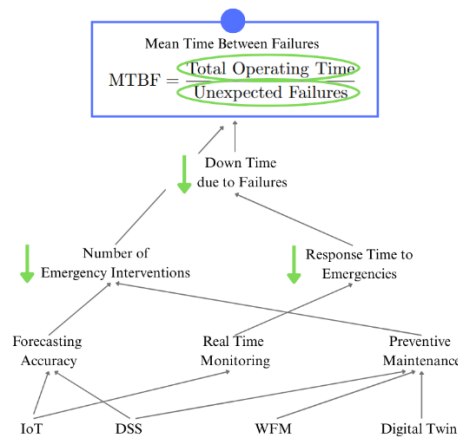


Figure 39: Mean Time Between Failures (MTBF) Individual Causal Path

- Mean Time to Detect (MTTD):** The deployment of IoT sensors across the water infrastructure provides the backbone for real-time monitoring, enabling the immediate detection of operational anomalies as they occur. These sensors ensure continuous oversight and generate alerts the moment predefined thresholds are breached, substantially shortening the interval between the occurrence and recognition of a failure.

Complemented by increased forecasting accuracy, which is achieved through the integration of DSS and IoT, the number of unexpected faults is reduced by flagging potential failures in advance. At the same time, preventive maintenance, supported by DSS, WFM systems, and the network digital twin, lowers the total number of critical events and allows interventions to be timed more effectively.

As a result, both the frequency of emergencies and the latency in recognizing them decrease, leading to an improvement in operational readiness and a lower Mean Time to Detect (MTTD).

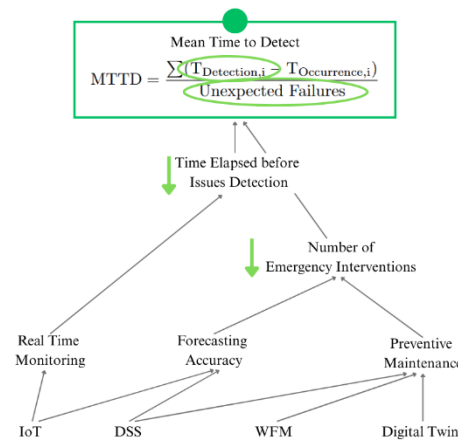


Figure 40: Mean Time to Detect (MTTD) Individual Causal Map

- **Recall:** By continuously observing system behaviour, IoT sensors provide real-time data that feed into predictive models within the Decision Support System and Digital Twin. These tools simulate infrastructure dynamics and apply analytical logic to distinguish early-warning signals from routine fluctuations, increasing the system's capacity to anticipate failures accurately.

In combination, these forecasting mechanisms and the preventive maintenance strategies, made possible by the DSS, WFM systems, and digital simulations, reduce both the number of emergency interventions and the share of undetected incidents. This dual outcome, constituted by better proactive detection and decreased number of unforeseen failures, improves the Recall rate, defined as the proportion of actual failures that were correctly predicted in advance. As detection coverage expands and forecasting precision increases, this KPI provides a critical measure of the system's ability to manage operational risks intelligently, an essential aspect of resilient, forward-looking governance.

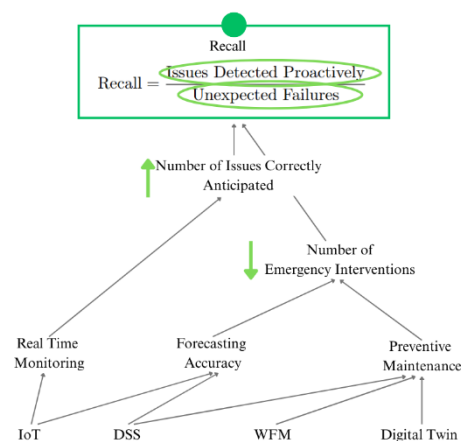


Figure 41: Recall Individual Causal Map

8 Model's Scalability and Transferability

8.1. Introduction

In spite of the fundamental aspiration that knowledge, once generated, does not remain confined to the boundaries of a single case but gets instead evolved into a shared instrument, this section aims at evolving the developed model beyond the limits of analysis and into generalizability.

What was originally conceived as a response to the complexity of a specific digital sustainability project here becomes a formalized method, capable of being reused, transferred, and adapted across different contexts, sectors, and domains. The ambition is rooted in the conviction that science, at its most valuable, does not stop at demonstration but continues into replication, adaptation, and refinement, facilitating the work of future researchers by formalizing what achieved by previous ones. The model's internal architecture, characterized by its multilayered causal logic and its hierarchical ESG anchoring, was in fact never intended to remain static but to serve as a tool that others could inherit, interpret, and apply in new and diverse scenarios.

By codifying its structure and offering guidance for its application, this section affirms the model's role as a methodological resource, a foundation upon which others can build, and a contribution not just to content, but to method. What follows is therefore a real practical effort to turn what was once a highly exploratory and time-consuming construction process into a clear, reproducible, and adaptable methodology for assessing the impact of digital technologies on sustainability outcomes.

8.2. Objectives and Purpose

The primary objective of this section is to ensure that the developed model can be effectively reused and extended by others, without requiring them to retrace the exhaustive process that originally led to its creation. Indeed, while the model was designed in response to a specific case, its structure reflects the broader ambition of serving as a reference tool for anyone attempting to assess the sustainability impacts of digital transformation projects through a rigorous and multidimensional approach.

Too often in research, especially in emerging or interdisciplinary fields, new methods are built in isolation, shaped by trial, error, and necessity, without becoming accessible

to those who come next. This section aims to break this cycle, offering a refined, ready-to-apply framework that reduces ambiguity, avoids redundancy, and accelerates the analytical work of future researchers, practitioners, or institutions. The purpose is not only functional but scientific as, by formalizing the method, this section contributes to the cumulative logic of research: what has been constructed once, after much effort, becomes available as a tool, replicable in its logic, transparent in its assumptions, and adaptable to different use cases.

Thanks to its flexible and customizable structure, the model is not to be seen as a rigid scheme, but rather as a framework for structured reasoning, one that can be interpreted, extended, and tailored to the specific characteristics of each project. In this way, it seeks to fulfil a dual purpose: to provide immediate utility for those conducting complex sustainability analyses in digital contexts, and to offer a step-by-step procedural guide that supports the concrete implementation of the model in real-world scenarios.

8.3. Application Procedure

To support the model's intended scalability, this section offers a streamlined and accessible implementation pathway, designed for researchers, students, and professionals who wish to apply the framework to new projects involving digital transformation and sustainability.

The original development of the model was intentionally exploratory, with each step questioned, tested, revised, and refined through trial-and-error, allowing for the emergence of a method that is both empirically grounded and conceptually rigorous. Exactly for this reason, however, the construction process was long, fragmented, and at times difficult to navigate, making all the more necessary the effort to eliminate ambiguity for those who follow and to transform a previously uncertain process into a clear, repeatable one.

The application procedure outlined here captures only the essential steps, those strictly necessary to reconstruct the model's core logic and produce a meaningful and coherent analysis. All remaining complexities, redundancies, and exploratory detours are deliberately excluded, taking care of simplifying the procedure while preserving the model's analytical power. Each step can be adapted to suit the user's goals and context, and while optional components such as narrative paths and stakeholder validation are encouraged to enrich the result, they are not required for the model to function effectively.

Whether the objective is academic research, strategic planning, or policy evaluation, this guide seeks to allow users to quickly generate a high-quality sustainability impact model.

8.3.1. Step 1: Contextual Understanding and Documentation Review

The first step consists in developing a solid and well-rounded understanding of the project to be analysed. This requires gathering and reviewing all available documentation, including internal reports, technical materials, public communications, and, when possible, direct stakeholder insights. The aim is to reconstruct the strategic and operational logic of the initiative, start identifying the digital technologies involved, and grasp the expected changes these technologies are meant to enable.

To guide this review, the following questions can be taken as reference: What is the rationale behind the project? What problem is it trying to solve, and through which strategic objectives? What processes are expected to be affected, and in what way? Which benefits, either operational, technological, or sustainability-related, are being explicitly pursued or implicitly suggested?

This phase is about documenting the system's components and intentions as clearly as possible, creating a reliable foundation for the following analytical steps.

8.3.2. Step 2: Identification of Technologies and Intrinsic Properties

Once the project scope has been thoroughly understood, the next step is to isolate and define the digital technologies integrated into the solution. These tools represent the foundational layer of the model and are the starting point from which all causal relationships will develop. It is therefore essential to identify each technological component clearly and to understand its functional role within the system, focusing not only on what the technology is, but on what it enables.

Within this step, the analysis should not limit to a simple listing of all involved solutions but should also and most importantly clarify which capabilities they introduce or enhance that could be beneficial for the project. Indeed, rather than limiting the description to technical features, attention should be given to the potential of each tool to generate transformation within the system. For instance, an IoT infrastructure should not only be noted for its presence, but for its ability to enable continuous real-time monitoring, granular data collection, and remote diagnostics. A DSS platform should be identified not just as a decision-making aid, but as a technology that unlocks scenario simulation, performance forecasting, and intervention prioritization.

The objective is to associate from the very beginning each technological component with the functional levers it introduces so that the analytical process can become significantly more immediate and manageable. By positioning each technology alongside its most relevant properties from the start, it becomes no more necessary to retroactively extract implications later in the process, and a smoother transition into pathway construction is enabled. Obviously, it must be remembered that many variables are not enabled by a single technology alone, but rather emerge from the integration and cooperation of multiple components within the system, as in the case of DSS and WFM Systems that together improve the organization of preventive maintenance. These functional synergies are at the heart of the model's causal structure, where variables should not be interpreted as isolated outputs of a single solution but product of technological interactions.

8.3.3. Step 3: Sustainability Impacts and KPI Selection

At this point, the focus shifts toward understanding which sustainability dimensions are potentially impacted by the project and how these impacts can be measured.

Areas of Impact

The first part of the analysis involves reflecting on the potential effects the project may generate across environmental, social, and governance dimensions, which does not yet require defining causal paths but rather capturing all plausible areas where change may occur. At this stage, the assessment should remain exploratory and inclusive, considering both direct and indirect impacts, such as reduced energy consumption or increased stakeholder trust resulting from improved reporting quality. Moreover, it is useful not only focus on certainly verifiable effects but also on potential ones, taking into account contextual factors and circumstances that may unlock additional results.

To guide this process, it is recommended to refer to a structured ESG framework with multi-level categorization, such as the one adopted in this study. This hierarchical structure, particularly its third-level subdimensions, helps ensure that the identified impacts are not overly generic but precisely anchored to established sustainability areas, which in turn makes it easier the choice of KPIs.

KPIs Selection

Once the potential impacts are mapped, the next task is in fact to translate them into Key Performance Indicators (KPIs): specific, measurable metrics able to reflect the change generated by the technological solution. The selection should prioritize indicators that are both relevant to the project context and methodologically sound, ideally supported by literature, regulatory guidelines, or company standards.

KPIs can be sourced from a variety of references, depending on the nature of the project and the information available. If the solution under analysis is implemented by a specific company or brand, internal documentation and reporting systems may already provide well-defined indicators tailored to the organization's operational and strategic priorities. Alternatively, relevant KPIs can be extracted from academic literature, especially in cases where prior studies have addressed similar technologies or sectors. Specialized documents and institutional reports, such as those issued by standard-setting bodies, regulatory authorities, or professional associations, can also serve as a valuable resource, particularly when alignment with global sustainability standards is required. In addition, the ESG framework developed in the previous chapters of this work provides a comprehensive and structured set of potential KPI categories, being particularly helpful when no predefined indicators are available or when a broader exploration of impacts is desired. By drawing from this diversified set of sources, users can in fact ensure that selected KPIs are both contextually appropriate and analytically robust, aligned with the identified sustainability dimensions.

As an additional note concerning the character of KPIs, it is obviously possible to select both quantitative and qualitative indicators, depending on the nature of the project and the availability of data. However, it should be acknowledged that the solidity and analytical depth of the final model will vary accordingly.

The model was originally developed to support a quantitative evaluation of the impact of digital solutions on sustainability, allowing for traceable, measurable, and comparable results across different contexts and over time. Quantitative KPIs generally provide a more rigorous foundation for drawing causal inferences and enable stronger validation of the relationships represented in the model. That said, qualitative indicators can certainly be integrated when appropriate, particularly in projects where measurable data is limited or where the impacts being assessed are inherently subjective, such as changes in employee satisfaction, stakeholder trust, or governance transparency. In such cases, the inclusion of well-structured qualitative metrics can still offer valuable insight, provided that their definition is consistent and that their position in the causal path is clearly justified.

KPIs Classification

Once selected, each KPI should also be classified to improve the interpretability and strategic focus of the model. Two complementary criteria are suggested:

- By nature of impact:
 - Certain & Direct: the KPI is influenced immediately and unequivocally by the implementation of a specific technology
 - Certain & Indirect: the KPI is impacted through a multi-step or mediated causal pathway, but its effect is still expected with high reliability

- Potential: the KPI is influenced by the project under specific contextual or enabling conditions, with a not guaranteed or universally replicable outcome
- By strategic relevance:
 - Core target: the KPI corresponds to an explicitly stated objective of the project and is central to its expected value creation
 - Collateral effect: the KPI reflects an unplanned but beneficial outcome, emerging as a secondary consequence of the technological implementation

8.3.4. Step 4: Construction of Causal Pathways

Once the technologies have been identified and the KPIs selected, the next step consists in constructing the logical structure that connects these two elements through a series of cause-effect relationships. The objective is to clarify how each technological enabler contributes to the achievement of one or more sustainability outcomes, making explicit the internal transformation process activated by the digital solution.

Even if during the original development of this model, causal pathways were first constructed individually (one per KPI) and only at a later stage merged into broader, dimension-specific diagrams, it is here suggested to proceed directly with the creation of a single aggregated chart for each ESG dimension. Indeed, although useful for exploratory purposes and essential in reaching the finalized structure of the model, the intermediate passage is not necessary for reproducing the model's formal outcome. If first- and second-tier variables have been correctly selected during the Step 2, the graphic description of individual causal paths may prove redundant and unnecessarily time-consuming. This more streamlined approach allows users to immediately highlight recurring patterns and reuse common variables, making the modelling process both faster and more consistent.

Structural Model Layering

Dividing the plane into five different layers, users are invited to follow the same top-down and bottom-up reasoning adopted for the original model's development, as it proved to be the most effective approach for delving into the core logic of the project and accurately reconstructing its internal mechanisms.

At the base of the diagram lie the digital tools identified in Step 2, recognized as catalysts of change in the system's configuration and operations. The tier immediately above is reserved for the associated tech-enabled characteristics, that is the direct properties and functionalities introduced by these technologies, such as real-time monitoring, anomaly detection, or automated data processing. Going then to the upper levels, KPIs, which populate the fifth layer, must be connected to their

corresponding impact variable placed in the tier immediately below. These concrete parameters, influenced by the digital solution, represent the first observable changes through which sustainability outcomes are quantified and monitored.

Identification of Operational Variables

What remains to be populated is the third layer, which plays a pivotal role in the architecture of the model. This level is dedicated to operational variables, defined as the system-level improvements made possible by the technologies and their enabled functionalities. They do not represent outcomes in themselves but describe how the system behaves differently after the intervention, including examples such as increased responsiveness, reduced number of emergency interventions, or better resource allocation. Fundamentally, they serve as key mediators in the cause-effect chain and are often responsible for linking multiple technologies to multiple impacts.

To identify these variables effectively, while also avoid redundancy and excessive diversification, users are advised to proceed progressively, focusing on a causal pathway at time and trying to extend its applicability. Starting from the first KPI, the most suitable operational variable(s) should be introduced in the third, empty layer based on the logic of cause effects enabled by the down standing technologies. Then, moving to the next KPI, users should assess whether the just inserted variable(s) can be used to also explain the new outcome: if yes, it is reused and linked accordingly, otherwise a new one is introduced. Following this method ensures that only a limited number of third-layer variables are needed to cover a wide range of effects, allowing for a compact, standardized, and reusable structure.

Connections Mapping

Once all required variables have been positioned within their respective layers, directional arrows can be drawn to connect them, tracing the logical flow from technologies at the base to KPIs at the top. Due to the non-redundancy and non-repetition principle adopted in the model's construction, most variables are expected to be connected to multiple upstream and downstream elements, with several arrows converging toward or diverging from the same point. This naturally leads to intersections within the visual layout, a feature that, it must be remembered, is not only accepted but reflective of the model's systemic logic and interconnected structure. The key is to ensure that, despite the overlapping of lines, the diagram remains visually clear and easily interpretable, a result achievable through proper spacing between layers, consistent arrow orientation, and the use of clean, direct paths.

Arrows are typically expected to move from one layer to the immediately adjacent one, maintaining a consistent logic of transformation across the structure, but exceptions

are possible and legitimate. In certain cases, an implemented technology may generate an operational effect directly, without passing through a clearly defined tech-enabled function, or may operate alongside another technology that follows the standard theoretical sequence—first enabling a functional property before contributing to the third-layer operational change. Likewise, some impact variables may be influenced directly by tech-enabled characteristics, as in the case of real-time monitoring that on its own increases the power consumption associated with the operation of the digital infrastructure.

Directional Impact Annotation

To improve the layout, each element in the third and fourth layers, which respectively host operational and impact variables, need to be accompanied by a small, coloured arrow symbol that serves a dual purpose:

- The direction indicates whether the variable is expected to increase (upward) or decrease (downward) in value
- The colour communicates whether this variation has a positive (green) or negative (red) effect in terms of sustainability

This simple annotation system allows users to quickly grasp both the nature and the desirability of each change, making the model more accessible for stakeholders and more powerful as a communication tool.

Visual Coding of KPIs Relevance and Reliability

Finally, as completion of the classification process begun in Step 3, each KPI should be visually annotated to reflect the nature of the impact in terms of certainty and strategic relevance. This is done through a set of intuitive graphical markers embedded directly within the diagram:

- A coloured outline is applied to the KPI node to indicate the level of certainty:
 - Green for certain and direct impacts
 - Blue for certain but indirect impacts
 - Yellow for potential impacts
- A circular marker is placed next to each KPI to signal its strategic intent:
 - A solid circle represents a core target
 - A hollow circle denotes a collateral effect

By integrating value judgments, likelihood, and strategic relevance directly into the visual layout, the model becomes not only a tool for analysis, but a platform for structured decision-making and clear stakeholder communication.

8.3.5. Step 5: Optional Additions

While the core structure of the model is completed with the layered diagram and its annotations, two additional activities can be included to further enhance the model's readability, transparency, and credibility. These additions are not mandatory for applying the methodology, but are strongly encouraged, especially in cases where the model is intended for external communication, stakeholder engagement, or academic dissemination.

Narrative Descriptions (Optional but Recommended)

To complement the visual layout, users are encouraged to include a short narrative explanation for each path within the ESG diagrams, placing them at the bottom of the structure in line with the reference KPI. These concise texts should describe, in a few lines, how the technologies introduced enable specific functions, trigger operational improvements, and ultimately influence the selected indicator.

Especially in cases where diagrams are heavily populated and multiple arrows intersect, these narrative descriptions can be used to enhance comprehensibility in the eyes of readers and preserve the individual logic of each path even in the presence of structural complexity.

Stakeholder Validation (Optional but Valuable)

When possible, the model should be reviewed with individuals directly involved in the project under analysis, including ESG managers, IT specialists, project leaders, or field operators, who can all provide critical contextual insights that may not be fully captured in the available documentation.

Validation sessions may help to confirm the accuracy and plausibility of the identified pathways, refine or reframe selected variables and impacts, adjust or validate the classification of KPIs, and increase internal acceptance and practical relevance of the model.

Although not formally required for model construction, interacting with stakeholders adds a valuable layer of legitimacy and precision, particularly when the framework is intended to inform real-world decision-making or institutional reporting.

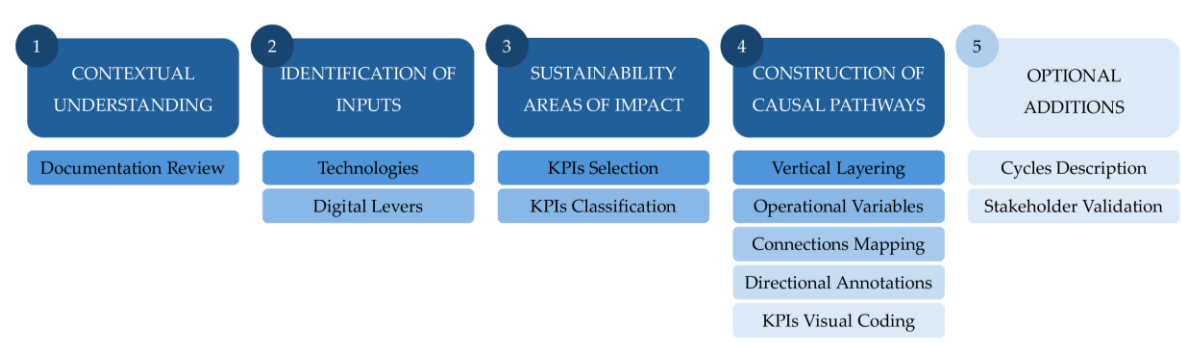


Figure 43: Guide for Methodology Application

8.4. Challenges and Common Pitfalls

While this guide offers a streamlined and structured path for applying the model, certain challenges and critical missteps may still arise during implementation, making it essential to anticipate potential obstacles to preserve the model’s rigour, consistency, and interpretability.

Building on experience, this section aims therefore to highlight the most frequent pitfalls encountered in early applications of the model and to offer practical suggestions for avoiding them properly.

Over-specification or over-generalization of variables

A common difficulty lies in finding the right level of granularity when defining variables, particularly operational ones. These are meant to represent tangible, observable shifts in how the system functions and serve as the crucial link between technological properties and company-level performance outcomes. Users may be tempted either to introduce overly specific, context-dependent terms that limit generalizability, or to rely on broad, abstract notions that fail to capture actionable change. To avoid this, operational variables should be clearly identifiable, functionally meaningful, and formulated in a way that allows for potential reuse across multiple pathways, neither too narrow to isolate, nor too vague to interpret.

Redundant or repeated elements

Despite the model’s non-redundancy principle, users may inadvertently reintroduce the same variable under different names or slight variations, especially if causal paths are designed in isolation or when terminology is not harmonized across the diagram. To prevent this, it is recommended to work from a progressively expanding, shared list of variables, constantly verifying whether a newly introduced concept is genuinely distinct or simply a reformulation of an existing one.

Excessive focus on the diagram over the logic

Especially when using visual tools, users may become overly focused on building the diagram as a graphic product rather than as a logical map of systemic transformation. The model should never become an exercise in aesthetic balance but, above all, a tool for analytical representation. If in doubt, clarity of logic should take precedence over visual symmetry.

Neglecting cross-functional integration

Digital solutions rarely act in isolation and one of the model's core principles is that technologies often work together to generate change. To avoid underestimating this aspect, which may lead to artificial separations between functions and to underrepresentation of synergistic effects, converging influences and eventually non-linear paths should be embraced.

At the same time, since multiple digital tools may theoretically contribute to the same tech-enabled variable, users should resist the temptation to link every relevant technology indiscriminately. Instead, each variable should be connected only to the most representative and functionally responsible technology(s), those whose role is clearest and most essential in enabling that function. The result is decreased clutter and improvement in the legibility and interpretability of the diagram.

By remaining attentive to these common pitfalls, users can avoid compromising the clarity and analytical strength of the model, ensuring that it remains not only a formal exercise but a meaningful tool for understanding and communicating the impact of digital transformation on sustainability outcomes. What this framework offers is a method, a scaffold, designed to support the reasoning behind it and to guide it toward coherence, transparency, and replicability. Its correct application ultimately depends not only on following the steps, but on approaching each with awareness, discipline, and adaptability.

9 Discussion of Results

9.1. Qualitative Assessment of ESG Impacts from the SMW Project

9.1.1. Introduction

After having described the model from a scientific and methodological standpoint, and having illustrated its concrete application to the Smart Water Management project developed by Al maviva, an additional and almost necessary step consists in commenting on the actually obtained results. Indeed, while the core objective of this thesis has not been to evaluate sustainability outcomes per se, but rather to design and validate a robust assessment framework capable of capturing the multifaceted impact of digital technologies on sustainability, the absence of a final reflection on the expected results would leave the analysis incomplete. As a matter of fact, once the model has been articulated and implemented in a real-world context, commenting on the emerging insights becomes essential to demonstrate the framework's practical value, its explanatory power, and its potential use for strategic decision-making.

From this perspective, the present section serves as a bridge between theory and interpretation, translating the structured causal architecture composed of first-tier technologies, second-tier digital levers, and third-tier operational variables into an interpretive reading of the sustainability implications that can be reasonably derived from the model. More specifically, focusing on the project under analysis, it expresses on how these internal dynamics activate or inhibit performance changes across the set of classified KPIs, examining dimensions with respect to the strength, nature, and intentionality of the impact each indicator is expected to experience as a consequence of the digital transformation introduced by SWM.

As a disclaimer, it is important to specify that, due to the lack of access to empirical datasets such as pre- and post- intervention values, the following evaluation will not be based on quantitative calculations and KPIs won't be numerically computed. Rather than constituting a limitation, however, this absence of data further highlights the flexibility and resilience of the model, as the ability to produce meaningful insights even in data-constrained contexts is achieved by leveraging the internal logic of causal chains and the known characteristics of the technologies involved.

In particular, the assessment of sustainability impacts presented in this chapter is primarily grounded in the classification of KPIs developed and illustrated in earlier sections, which was not arbitrarily defined but emerged from both the scientific literature and a series of brainstorming sessions held in collaboration with the project's responsible stakeholders. Through this process, each KPI was assigned a set of qualitative attributes concerning degree of certainty and intentionality of the expected impact, allowing the model to generate a coherent interpretation of how the Smart Water Management initiative influences ESG performance. Rather than relying on direct numerical measurement, the following evaluation leverages the framework's internal consistency and the prior classification work as its primary interpretive tool, offering a high-level yet analytically sound overview of the system's sustainability implications.

Ultimately, this chapter is not merely an appendix to the model, but a demonstration of its operational capacity, as it illustrates how the framework can be used to interpret and anticipate sustainability outcomes even in the absence of numerical data. Even if highly encouraging the reliance on quantitative information, when available, the following discussion offers a viable method for assessing digital initiatives in contexts where real-time monitoring or precise measurement remains out of reach. Emphasis is therefore given to the claim that sustainability assessment requires not only accurate data but also structured reasoning, capable of connecting technological choices to long-term ESG performance through a rigorous and transparent methodology.

9.1.2. Dimension-Specific Results

9.1.2.1. Environmental Dimension

Among the three ESG areas analysed, the environmental dimension is arguably the one where the Smart Water Management (SWM) project exerts the most immediate and visible effects. This is partly due to the intrinsic nature of the intervention, which is focused on infrastructure optimization, resource efficiency, and system intelligence, and to the long-standing, widely acknowledged connection between environmental sustainability and technological modernization in the utility sector. As such, many of the KPIs analysed in this section are not only strongly impacted by the digital transformation introduced, but were also explicitly considered during the design of the solution.

As already detailed in previous chapters, the environmental dimension has been articulated around two second-level categories: climate change and resource utilization, which respectively focus on the direct and indirect consequences of the project on greenhouse gas (GHG) emissions and the changes in the efficiency with which water, energy, and materials are used throughout the system. While some impacts emerge as clear and intentional results of technological functionalities, others

represent collateral and sometimes unintended effects, requiring careful consideration and proactive mitigation.

Within the climate change category, two contrasting dynamics emerge. On one side, the CO₂ emissions from field interventions (CO₂-FI) are expected to decline as a result of reduced emergency maintenance and more efficient task scheduling, representing a certain and positive outcome, albeit indirect and unintended. On the other side, CO₂ emissions from digital infrastructure (CO₂-DI) are likely to increase, reflecting the higher energy demand introduced by always-on systems and cloud platforms. This impact, negative in nature, remains context-dependent and unintentional, highlighting the common trade-off in digital sustainability for which increased intelligence may come at the cost of greater energy use, especially in carbon-intensive energy mixes.

In the area of resource utilization, the intervention achieves clearer and more intentional benefits, as both the Percentage Leakage Index (PLI) and the Pipeline Efficiency Index (PEI) are expected to show definite improvements, reflecting the project's core aim of reducing water losses and optimizing hydraulic performance. These KPIs are indeed directly and positively affected by the system's functionalities and are recognized as strategic targets. More nuanced are instead the results related to energy and material consumption because, while Technological Energy Consumption (TEC) is expected to rise, manifesting its collateral and potentially negative effect, Total Material Consumption (TMC) presents a dual trend that depends on how the company handles its operations. The deployment of physical infrastructure initially increases material demand, especially if circular economy techniques are not embraced, while the reduction of emergency interventions potentially lower the need for field repairs and associated resources.

Overall, the environmental results portray a balanced but asymmetrical landscape, with most KPIs reflecting clear and positive progress on core targets such as leakage and efficiency and only a few revealing emerging trade-offs typical of digitalization processes, particularly regarding energy and material flows.

9.1.2.2. Social Dimension

While the Smart Water Management (SWM) project was not originally conceived with a primary focus on social sustainability, its implementation introduces a number of significant effects on the human and organizational components of the utility system. The latter can be both certain and advantageous, ranging from improved access to water services to better working conditions, but also potentially damaging, as in the case of cybersecurity threats and the emergence of new digital-related risks. The relevance of the social dimension lies in the fact that, despite not being a central design driver, the SWM system unintentionally reshapes workforce dynamics, citizen

experiences, and internal management practices—thereby positioning itself as an enabler of broader societal change.

Within the access to resources category, the Water Source Availability (WSA) index stands out as a core target that is expected to improve significantly thanks to the minimization of service disruptions through predictive and preventive mechanisms. As a consequence of fewer emergency breakdowns, the system is in fact expected to increase the continuity of water supply—an outcome that, while indirect, is both certain and highly relevant from a social equity standpoint.

In the domain of education, instead, the Technical Training Rate (TTR) is also expected to rise, as the growing complexity of the digital ecosystem requires staff to acquire new technical skills related to system monitoring, data interpretation, and digital troubleshooting. This effect, though not planned as a strategic outcome, emerges as a direct and positive transformation, a collateral benefit that supports workforce upskilling and adaptation.

With respect to work and income, the Rate of Work-Related Injuries (RWRI) is projected to decrease thanks to the system's shift from reactive interventions to proactive maintenance, which overall reduces technicians' exposure to emergency scenarios and hazardous conditions. The impact is therefore certain and positive, indirect since mediated by the way the company decides to manage its business but perfectly aligned with one of the core values of sustainable organizational practices: the protection of employee well-being.

Moving into the security cluster, however, two contrasting effects are observed. On the one hand, Water Quality Compliance (WQC) benefits directly from the integration of real-time monitoring tools, which detect anomalies early, prevent contamination risks, and reinforce service reliability and safety. On the other hand, the introduction of pervasive digital infrastructure raises concerns around cybersecurity and system vulnerability, with both System Vulnerability (SV) and Remote Access Control (RAC) showing potential exposure to risks if security protocols are not adequately configured or maintained. While these effects are not guaranteed to materialize, they represent plausible negative outcomes that should never be understated and whose presence underscores the importance of always embedding security-by-design principles in smart infrastructure projects.

Overall, the social results illustrate a strong alignment between digital transformation and improved human conditions, particularly in terms of access, training, and safety. At the same time, they highlight the emergence of new vulnerabilities linked to digital complexity and the need for governance systems that can anticipate and mitigate associated risks. In this sense, the social dimension reveals how technological modernization, even when not explicitly aimed at societal outcomes, can generate tangible improvements in quality of life, demanding only new forms of organizational responsibility in return.

9.1.2.3. Governance Dimension

Unlike environmental and social dimensions, where the outcomes of the Smart Water Management (SWM) project are often tangible and externally visible, the governance dimension reflects changes that are primarily internal to the organization. These impacts pertain to the quality of decision-making, the transparency of operations, and the robustness of risk management mechanisms, all of which are crucial for ensuring long-term sustainability, even if less immediately perceptible.

In digitally enabled infrastructures such as SWM, governance improvements are typically linked to the system's enhanced ability to generate, structure, and disseminate information, as well as to anticipate operational risks through predictive capabilities. The selected KPIs for this dimension, primarily distributed across the categories of communication and risk management, were therefore chosen precisely to capture these features, and are evaluated here based on the qualitative classification previously developed in collaboration with project stakeholders.

Under the communication category, the Potential Utility (PU) indicator shows a clear and unequivocal improvement, as the integration of IoT, analytics platforms, and business intelligence dashboards ensures that relevant, structured, and decision-ready information is continuously available to managers and technical teams to reduce information asymmetries and enable more transparent, evidence-based choices.

In the area of risk management, the results are equally encouraging, with all the selected KPIs significantly improving after the digitalization of processes and systems. The Proactive Work Ratio (PWR), for example, shows a definite upward trend, as emergency interventions are replaced by planned and data-informed maintenance activities that lead to greater control over operational processes and improved preparedness. Further reinforcement then comes from indicators related to system reliability and responsiveness, as both MTBF and MTTD are expected to improve reflecting the system's enhanced ability to detect anomalies early and mitigate stress factors before they lead to breakdowns. Finally, the Recall metric, designed to capture the solution's predictive accuracy in anticipating failures, is also projected to rise, underscoring the maturity of the project's digital intelligence layer.

In summary, the governance dimension reflects a set of systemic and foundational improvements that are driven by the enhanced informational, analytical, and predictive capabilities introduced by the digital architecture. Unlike the environmental and social dimensions, where certain trade-offs or collateral risks may emerge, no negative or unintended effects are here expected to occur and all variations are associated with improvements. The reason why is likely to be found in the nature of the impacts involved, which arise from interventions that, rather than altering external conditions or human behaviours, primarily enhance internal decision-making, processes operational oversight, and system intelligence, reinforcing existing organizational structures without generating new risks or inefficiencies.

9.1.3. Overall Considerations

Taken as a whole, the results emerging from the application of the proposed model to the Smart Water Management (SWM) project allow for a comprehensive and structured assessment of the initiative's expected sustainability performance. Despite the absence of empirical data and the inability to compute KPIs numerically, the qualitative interpretation provided across the three ESG dimensions reveals a scenario that is both balanced and largely positive, with most indicators pointing toward improved sustainability outcomes.

In the environmental dimension, results are mixed but largely encouraging, with core objectives such as leakage reduction and pipeline efficiency showing clear and intentional improvements, while a few collateral trade-offs such as increased energy consumption and material use highlighting the need for continuous optimization and mitigation strategies. From the social perspective as well, the project generates a wide range of positive effects, with potential risks emerging only in the areas of cybersecurity and system exposure and remaining actually easily manageable through appropriate safeguards and proactive governance. In this regard, it is exactly the governance dimension to emerge as the most consistently positive, with all selected KPIs showing clear improvements and no foreseeable negative impacts.

Crucially, one of the most significant insights produced by this assessment lies in the breadth and distribution of effects across all three ESG dimensions. Indeed, while the project was initially designed with a primarily environmental focus, the model demonstrates that digital interventions inevitably produce ripple effects that extend far beyond their original scope to trigger areas of sustainability never thought could be interested. In this case, the SWM system unintentionally reshapes organizational culture, workforce dynamics, public health safeguards, and governance structures, highlighting the deeply interconnected nature of sustainability.

This finding reinforces the insight according to which it is utopian to assume that any project, initiative, or technological solution can affect only one dimension of sustainability in isolation. On the contrary, environmental, social, and governance impacts are inherently entangled, and any attempt to address one without considering the others is likely to result in blind spots, unintended consequences, or missed opportunities. In this regard, the application of the model confirms not only its internal coherence and operational flexibility, but also its strategic value, as it enables a structured, comprehensive, and methodologically sound interpretation of complex sustainability transformations, even in the absence of granular data.

9.2. Methodological Affinities with Other Models

9.2.1. Introduction

As part of the broader discussion of results, this chapter offers a methodological interpretation of the developed model by situating its core elements within the wider landscape of existing modelling approaches. The objective is not only to trace conceptual precedents and identify methodological affinities, but also to demonstrate how the model engages with and contributes to current methodological debates, such as those surrounding the representation of causality, the integration of quantifiable metrics, and the treatment of complexity within system models. At the same time, it seeks to show how the model responds to a number of known limitations found across traditional frameworks, including issues of oversimplification, poor traceability, and lack of operational clarity.

Each component, ranging from its sequential layering and causal logic to its use of KPIs and impact typology, is examined in relation to the four methodological families identified in the earlier review: Theory-Based Models, System Dynamics and Participatory Models, Structural and Statistical Causal Models, and Evaluation and Prioritization Frameworks. Through this lens, the chapter provides a comparative validation of the model's architecture, clarifying its hybrid nature and evidencing how it consolidates, formalizes, or advances modelling practices already used in sustainability research and reporting.

9.2.2. Analysis of Elements

Multilayer Sequential Structure

A key feature of the proposed model is its multilayer sequential architecture, articulated in seven distinct levels through which each variable appears only once, even when functionally connected to multiple downstream elements. This structural clarity ensures traceability, avoids duplication, and enables a fine-grained analysis of causal propagation across the sustainability system.

From a methodological standpoint, Theory-Based Models partially reflect this approach through their reliance on a sequential logic of transformation, particularly visible in both the Logic Model [117] and Theory of Change [120]. However, their layering is generally limited to broad stages, such as inputs, outputs, and outcomes, without the internal granularity or strict level-by-level distinction observed in the developed model [119]. Furthermore, while the Theory of Change allows a certain degree of structural flexibility, it does not enforce a consistently bottom-up stratification, and often builds from impacts backward to original causes [122], rather than defining progression from the latter toward the final outcomes.

System Dynamics and Participatory Models, on the other hand, typically reject rigid layer-based architectures in favour of cyclical and distributed configurations. In Causal Loop Diagrams and Fuzzy Cognitive Maps, variables float within a network of interdependent loops, often reappearing at different points in the system to represent recursive dynamics [130, 133]. While this enhances the capacity to capture feedback and complexity, it sacrifices hierarchical clarity and introduces difficulties in isolating sequential influence chains. In contrast, the proposed model favours interpretability and linear causality, better suited to contexts where strategic planning and responsibility tracking are essential.

Models from the Structural and Statistical Causal family, such as the Causal Pathway Model or Structural Equation Models, often depict causal flows that can be layered, but are typically designed for hypothesis testing and do not prescribe a fixed stratification logic. Nodes are positioned based on empirical or theoretical logic rather than architectural symmetry, and it is common for variables, especially mediators or latent constructs, to appear in multiple roles or paths. The proposed model diverges here by enforcing non-redundancy and vertical coherence, favouring a single-point representation for each element, which strengthens both readability and alignment with system design principles.

Finally, Evaluation and Prioritization Frameworks such as IOOI and AHP support some form of logical ordering, especially in IOOI's linear chain from inputs to impacts [144]. However, these models are typically limited to four or five stages and do not offer a deep stratification or fine-grained layering of variables. Their orientation is primarily toward accountability and decision support, lacking the structural sophistication and multi-tiered causal tracking embedded in the present framework.

In conclusion, the seven-layer structure adopted by the model positions it as a hybrid solution, more granular and systematically layered than Theory-Based or Evaluation models, more interpretable than loop-based System Dynamics structures, and more architecturally disciplined than empirically driven Structural models. This configuration supports both diagnostic depth and navigability, two features essential to addressing the methodological gaps identified in existing sustainability assessment approaches.

Causal Nature

The proposed model adopts a deterministic and unidirectional causal logic, where each variable is explicitly connected to one or more outcomes via directed arrows that map the progression from enabling digital technologies to ESG outcomes through intermediate operational effects. Intentionally excluding loops, feedback cycles, or bidirectional influences, the goal is to provide a transparent, traceable path of influence that supports both interpretability and accountability.

Within the Theory-Based Models, causality is likewise made explicit, but these frameworks typically operate at a more aggregated level, often generalizing relationships between broad categories (e.g., inputs to activities) [117] rather than specifying direct interactions among discrete variables. Moreover, the Theory of Change relies heavily on the inclusion of narrative assumptions and contextual preconditions, which increases its flexibility but reduces its determinism [120]. Compared to them, the proposed model tightens causal inference by avoiding speculative links and mapping only those influence chains that are explicitly supported by the model's structure.

In contrast, System Dynamics and Participatory Models adopt a more fluid interpretation of causality, as they emphasize reciprocal influence, feedback, and circularity and consequently allow variables to simultaneously act as causes and effects within complex networks [131, 133]. However, while this makes them well-suited for exploring dynamic behaviours and emergent properties, it also complicates the isolation of one-directional causal flows, which is instead prioritized by the developed model so to clarify directional influence and attribution.

Structural and Statistical Causal Models, such as the Causal Pathway Model or Structural Equation Modelling, share the deterministic ambition of the proposed approach and formalize cause-effect relationships through testable hypotheses and emphasize intermediate mediation paths, often visualized through directed arrows [127, 141]. However, they frequently incorporate moderators or external variables to account for conditional effects [126] and may reuse variables across pathways.

As for Evaluation and Prioritization Frameworks, models belonging to this category are not inherently causal and therefore heavily differ from the fundamental structure of the developed framework. IOOI, for example, presents a logical sequence from input to impact [143] but does not enforce empirical validation of causal links or define directional arrows between individual variables, while, similarly, AHP and ANP rely on influence scoring and preference weighting rather than structured causal inference. These models support prioritization and evaluation but lack the explicit, variable-to-variable traceability that is the essential backbone and reason why of the model.

In summary, the deterministic and unidirectional causal logic adopted by the model finds its closest parallels in Structural Causal Models, such as the CPL, which similarly emphasize explicit, testable connections between variables through directed arrows. A comparable structure is also partially reflected in Theory-Based Models, particularly the Theory of Change, where sequential reasoning and articulated pathways are used to map the logic of transformation. The developed model builds on these foundations by reinforcing structural rigor, eliminating speculative assumptions, and enforcing a transparent flow of causality that enhances traceability across sustainability pathways.

One-to-Many Relationships

In order to capture real-world complexity, where a single factor can concurrently affect multiple operational outcomes or ESG impacts, the model allows each variable to serve as the origin of multiple downstream causal links, all represented explicitly via individual arrows. Crucially, each relationship is visualized separately, enabling non-redundant yet comprehensive impact tracing across the model's architecture.

Among the Theory-Based Models, this capability is only partially mirrored. The Logic Model often generalizes relationships between broad categories (e.g., "inputs" to "activities"), and while these can imply multiple effects, they are rarely mapped at the level of individual, differentiated connections [117]. The Theory of Change fares slightly better, occasionally adopting tree-like structures with branching logic, but it usually emphasizes many-to-one or convergent chains that link multiple precursors to a single outcome, rather than articulating how one node may influence diverse results [122].

In contrast, System Dynamics and Participatory Models naturally accommodate multiple directional links per variable [130, 135, 140, 154], as they are typically designed to represent dense connectivity and therefore allow nodes to have multiple incoming and outgoing arrows, sometimes even forming self-reinforcing feedback structures. However, the free-floating arrangement of variables across the diagram often results in visual clutter and reduced interpretability—challenges that are effectively mitigated in the proposed model through its vertically structured and upward-oriented layout.

Within Structural and Statistical Causal Models, one-to-many causal representations are analytically central. For example, in a Causal Pathway Model, an intermediate variable can influence multiple downstream outcomes, and these links are frequently formulated and tested statistically [127]. However, these models are often more interested in quantifying the strength or significance of paths [141] than in structurally capturing the dispersion of influence across multiple targets and therefore, while conceptually aligned, they typically lack the modelled structure's strict enforcement of graphical distinctiveness for each causal link.

Lastly, Evaluation and Prioritization Frameworks such as IOOI and AHP do not structurally represent one-to-many logic at the variable level, as they either imply sequential progress from inputs to impacts without detailing how one item may branch into several effects [144] or focus on deriving priority scores rather than visualizing causal dispersion [149, 151].

In summary, the model's explicit support for one-to-many causal mapping bridges a gap between the expressiveness of System Dynamics and the rigor of Structural Models, while significantly advancing the clarity and structural discipline absent in Theory-Based or Evaluation approaches. Overall, this design choice reinforces its

diagnostic precision, enabling the analysis of cascading effects from single interventions across multiple sustainability dimensions.

Uniqueness of Variables

A distinctive feature of the proposed model is that each variable appears only once, regardless of how many causal relationships it participates in, ensuring a non-redundant, hierarchically coherent structure in which every element occupies a well-defined position along a single vertical axis. As a result, the model maintains high levels of interpretability, visual clarity, and causal traceability, even in the presence of complex interdependencies.

Within the Theory-Based Models, this principle finds partial correspondence as in the Logic Model variables such as inputs, outputs, and outcomes generally appear only once, despite being linked to multiple others [119]. In the Theory of Change, instead, variables like intermediate outcomes may be repeated across different causal strands, especially when they contribute to multiple intended impacts [125].

In System Dynamics and Participatory Models, duplication is a common strategy used to resolve visual or conceptual complexity, with variables often reinserted multiple times within feedback cycles or across clusters either to facilitate readability or to emphasize their recurrent role in systemic behaviours [123]. While this flexibility enables richer system mapping, it compromises hierarchical discipline, making it difficult to establish a unique point of reference for each element and weakening the ability to conduct consistent causal tracing.

Structural and Statistical Causal Models offer a more diverse picture because, while formal representations such as Structural Equation Models rely on distinct variables within a defined causal matrix [141], Causal Pathway Diagrams may visually repeat elements for layout purposes, especially where variables mediate several downstream paths [123]. Indeed, even if the underlying statistical model avoids redundancy, its graphical representation may not enforce it, potentially introducing ambiguity in complex diagrams. In contrast, the proposed model makes non-repetition a core structural rule, ensuring that each concept can be clearly located and interpreted within its specific level.

As for Evaluation and Prioritization Frameworks, these models typically avoid duplicating variables, but not necessarily by design. In frameworks like IOOI, for example, variables are aggregated into stages, and their uniqueness results more from the simplicity of the structure than from a deliberate modelling choice. Similarly, AHP and ANP tend to represent variables and criteria only once within their hierarchical or network structures, but this reflects their focus on preference elicitation and weighting, rather than on mapping causal relationships. As such, the absence of duplication is functional to decision consistency rather than structural traceability, and these models

do not enforce or require a one-time placement of each variable for interpretative or analytical reasons [149].

In sum, the model's principle of assigning each variable a single, non-recurring position finds partial alignment with the Logic Model, where inputs, activities, and outcomes are typically represented once within a clearly segmented flow, and in Evaluation Frameworks like AHP and IOOI, where variables tend to appear only once, though primarily for simplicity and decision coherence rather than structural purposes. The proposed model formalizes this design choice as a core modelling rule, transforming what is incidental in other frameworks into a deliberate strategy for enhancing traceability, interpretability, and structural coherence.

Atomic Node Representation

In the proposed model, each variable or concept is treated as a distinct, non-aggregated node, rather than being subsumed within broad functional blocks or abstract categories. It is exactly this atomic representation to ensure that every unit in the causal structure corresponds to a clearly identifiable element, either measurable or definitional, and to consequently enable precise tracking, targeted interpretation, and unambiguous linkage across the entire chain of influence. Having the goal to clearly map the causal paths that lead from technologies to impacts, highlighting intermediary contributors and enablers, this model's characteristic appears as essential and unavoidable, typical of many but not all the analysed methodologies.

Within theory-based models, for example, atomic representation is inconsistently applied, with Logic Model tending to aggregate variables into macro-blocks where individual components are grouped for visual clarity and causal relationships are drawn between clusters rather than between specific, traceable variables, consequently limiting the analytical granularity of the model [118]. By contrast, even if the focus is on narrative coherence and assumption tracking, most developed versions of the Theory of Change happen to use discrete boxes for each outcome or intermediary condition, allowing better interpretability and lower generalization [120].

In System Dynamics and Participatory Models, instead, atomic node representation is definitely more standard, with models such as Causal Loop Diagrams and Fuzzy Cognitive Maps typically depicting each variable as an individual node, connected through weighted or directional links [130, 133, 143, 154]. At the same time, however, these representations often include abstract or hybrid concepts that may bundle several underlying phenomena into one node [131], which obviously allows to enhance model flexibility and stakeholder engagement but at the expenses of precision in analytical traceability and quantitative assignment. The proposed model avoids such conceptual aggregation, favouring a consistent, decomposed structure better suited for KPI-based analysis.

Structural and Statistical Causal Models generally adhere closely to atomicity, especially in Causal Pathway Diagrams, where nodes correspond to empirically testable or theoretically discrete variables and hypothesis testing and indicator assignment are therefore supported [126].

As for Evaluation and Prioritization Frameworks, atomicity is not a core feature. IOOI model treat variables in bundled form within broad categories, while AHP and ANP introduce individual elements within hierarchies or networks just for their role as criteria for preference comparison rather than analytical units within a causal mechanism.

In conclusion, the model's commitment to atomic node representation aligns most closely with Causal Pathway Diagrams and System Dynamics and Participatory Models, such as Causal Loop Diagrams and Fuzzy Cognitive Maps, which all routinely depict system elements as individual nodes. Additionally, more refined versions of the Theory of Change apply a similar logic by representing each outcome or precondition as a distinct box. Building on these precedents, the model formalizes atomicity as a structural design rule, reinforcing the precision and traceability required for robust sustainability analysis.

Signs and Variations Overview

As mentioned in previous chapters, the proposed model integrates a visual system of directional signs to indicate whether each variable is expected to increase (↑) or decrease (↓) as a result of upstream influences. Importantly, these symbols are placed directly next to the impacted variable at both drivers and operational outputs levels and are then colour-coded using green for positive changes in terms of sustainability and red for negative ones. This approach ensures that both the direction and desirability of each change are made explicit, enhancing both interpretability and evaluative clarity within sustainability-driven analysis.

In contrast, Theory-Based Models such as the Logic Model and the Theory of Change rarely incorporate explicit signs to denote either the direction or the qualitative nature of a change, as the displayed flows are typically assumed to be inherently beneficial, without any formal indication of polarity or context-specific desirability [119]. The Theory of Change, in particular, emphasizes causal assumptions but not the valuation or measurement of effect signs, thereby limiting its applicability when trade-offs or negative impacts must be assessed [120].

System Dynamics and Participatory Models offer a more advanced handling of sign and directionality, with +/- signs usually assigned to arrows to signal the polarity of influence (e.g., reinforcing vs. balancing feedback) [132]. However, these signs are not attached to the receiving variables but to causal links [134], and their interpretation is mathematical rather than normative, as they indicate whether a variable increases or

decreases another but not whether such variation is good or bad in sustainability terms. Moreover, even when fuzzy weights (ranging from -1 to +1) are used to quantify the strength and direction of influence, no semantic judgment or colour coding is provided to clarify whether an outcome is desirable or undesirable [133].

Some Structural and Statistical Causal Models, such as the Causal Pathway Model, may encode sign polarity, but do so analytically or textually, often for the purpose of empirical validation [126]. Like the dynamic models, they typically attach signs to causal arrows and use them in a neutral, descriptive sense [127], as the signs denote mathematical direction (positive or negative coefficient), but do not express any judgment of sustainability value or interpretive implication.

Finally, Evaluation and Prioritization Frameworks do not typically handle sign polarity or directional change at the variable level, as the focus lies in classification, comparison, or weighting, rather than in simulating or interpreting the effects of variation. These tools are well suited for ranking alternatives but are ill-equipped to convey how a change propagates through a system or whether it yields positive or negative sustainability consequences.

Summarizing, the model's system of visual signs and colour-coded desirability draws partial methodological precedent from System Dynamics and Participatory Models, where polarity is indicated through +/- signs on causal links. A more analytical, but structurally aligned, parallel can also be found in Structural Causal Models like the Causal Pathway Model, where sign direction is embedded in the logic of causal effects, albeit without normative interpretation. The proposed model advances these approaches by integrating polarity and sustainability judgment directly at the variable level, creating a unique convergence of directionality and evaluative clarity.

Quantification of Analysis through KPIs

Creating a link with the first part of the work, which addressed the issue of sustainability assessment, the furtherly developed model concludes each causal pathway with a set of quantifiable Key Performance Indicators (KPIs) aimed at measuring the real-world effects of digital enablers across sustainability dimensions. These KPIs are not generic but rather linked explicitly to individual variables within the model, serving as the analytical endpoints of each influence chain. In this way, abstract sustainability goals are translated into measurable, evidence-based metrics, supporting both comparison, performance evaluation, and monitoring over time.

Within the Theory-Based Models, the Logic Model and Theory of Change acknowledge the usefulness of KPIs, but often treat them as optional or loosely connected components, giving them scarce attention compared to other more central characteristics. While Logic Models can incorporate indicators for outputs and outcomes, these are typically included to demonstrate general program effectiveness

[137], not to provide granular, variable-level quantification. Similarly, even if Theory of Change encourages alignment with success metrics, its structure remains predominantly qualitative and narrative [124], especially in development and planning contexts. Compared to these, the proposed model imposes systematic quantification as an integral requirement, embedding KPIs at the end of each causal arc to enforce accountability and comparability.

Most of System Dynamics and Participatory Models tend to be qualitative by default, but examples such as Causal Loops can be easily enriched with numerical data by extending them into Stock and Flow Diagrams that require complex simulations and computational tools [138]. On the other side, Fuzzy Cognitive Maps introduce numeric fuzzy weights between variables only to describe influence strength rather than performance measurement in real-world terms, making them lose the importance and significance attributed by the presented model [135].

Looking at Structural and Statistical Causal Models, with a specific focus on Causal Pathway Models, they are inherently conducive to KPI integration, being able to include both quantitative and qualitative indicators to validate causal assumptions and measure impacts empirically [126]. However, similarly to before, these metrics are typically treated as data sources for validation rather than as intrinsic features of the structural representation. On the contrary, the proposed model goes a step further and tries to embed quantification directly into its design logic, making KPIs a structural output of each node rather than a separate analytical tool.

Where quantification through KPIs receives the most consistent attention is within Evaluation and Prioritization Frameworks, which routinely employ both qualitative and quantitative indicators to compare scenarios and assess trade-offs [145]. Typically linked to impact categories or performance dimensions, rather than being embedded within a detailed causal structure, these KPIs are used to facilitate decision-making, support priority setting, and enable transparent evaluation across multiple criteria [143].

Even if no existing methodology embedded KPIs as intrinsic endpoints within the causal architecture, relevant precedents can be found in Structural Causal Models, particularly Causal Pathway Models, where indicators are used to empirically validate causal relationships and assess impact, and Evaluation and Prioritization Frameworks, such as IOOI, which consistently adopt KPIs to support performance monitoring and scenario comparison across sustainability dimensions. The proposed model fundamentally builds on these approaches by transforming KPIs from external validation tools into structural components of the model itself, thereby enhancing alignment between causal reasoning and measurable outcomes.

Impact Categorization

The proposed model introduces an explicit and visually embedded classification of impact types, distinguishing whether the influence of a digital technology on a given KPI is direct, indirect, or potential, as well as deliberately researched or unintentionally achieved. This categorization is not abstract or textual but is reinforced through color-coding and symbolism, enabling users to rapidly assess the reliability and proximity of each sustainability impact. It supports prioritization, interpretation, and communication, particularly in contexts where differentiating the strength and certainty of causal effects is essential for decision-making and accountability.

Among the Theory-Based Models, this exact kind of distinction is not typically embedded, but it can be inferred with variances. The Logic Model, for instance, separates activities, outputs, outcomes, and impacts primarily based on time horizon, not on causal depth or strength [117, 118], while the Theory of Change can provide interesting and similar insights when distinguishing impacts in immediate and observable, arising only via preconditions or assumptions, and context-sensitive effects [124]. However, such distinctions tend to be narrative rather than structural, and they are seldom visualized in a consistent way across the diagram.

Causal Pathway Models, instead, offer a more robust basis for differentiating between types of impacts, as they often distinguish between immediate effects (direct), those mediated through intervening variables (indirect), and distal effects (potential), particularly in the context of hypothesis testing [129]. Nevertheless, while conceptually precise, these distinctions are often expressed verbally or through model logic, without any embedded visual language to support intuitive communication of impact reliability.

In contrast, System Dynamics and Participatory Models rarely differentiate between direct, indirect, or potential impacts in any formal sense, as their focus lies on feedback structures and network dynamics, where the location of a variable within a loop carries more significance than its categorical proximity to impact. FCMs do express variation in strength through fuzzy weights, but they do not codify the type of effect, and their outputs are better suited for exploring systemic complexity than for assessing certainty or immediacy of impacts [133].

Evaluation and Prioritization Frameworks, particularly those in environmental impact assessment, are more attuned to impact classification, often incorporating direct, indirect, and potential effect ratings while potentially applying colour scales to assess severity or relevance [136]. On the other hand, these classifications are generally disconnected from explicit causal pathways and are applied after impact identification, not during causal mapping.

Ultimately, while no existing methodology structurally embeds impact categorization into the causal model with visual coding, similarities can be recognized between the developed model and both the Theory of Change, which introduce narrative

distinctions among immediate, assumption-based, and context-sensitive outcomes, and Causal Pathway Diagrams, which analytically differentiate between direct, indirect, and distal impacts. Additionally, Environmental Impact Assessment frameworks routinely classify effects by proximity and relevance, often using colour coding for severity. The proposed model consolidates and advances these approaches by integrating impact typology directly into the architecture, ensuring that causal clarity is paired with evaluative precision.

Cycles Description

For further improving readability and interpretability, each causal chain is accompanied by a textual explanation that clarifies the logic, rationale, and functional relationships among the variables along the path. These narratives serve to articulate how and why certain technologies generate sustainability impacts, enhancing the comprehensibility of the model and reinforcing its transparency and accountability. Moreover, the written descriptions also enable users to engage in evidence-based evaluation of each chain, ensuring that the causal pathways are not only visually intuitive but also conceptually grounded.

This approach aligns most closely with Theory-Based Models, particularly the Theory of Change, which is explicitly designed to combine diagrammatic representations with narrative articulation of assumptions, preconditions, and logical flow. In such models, explanatory text is essential to validate the sequence of events, justify causal expectations, and communicate the reasoning behind the anticipated outcomes [120].

A similar textual dimension is also present in some applications of Evaluation and Prioritization Frameworks, where written justifications often accompany quantified results to contextualize decisions or explain the basis for certain impact evaluations. However, these descriptions are usually retrospective rather than embedded into a causal chain.

By contrast, System Dynamics, Participatory Models, and Statistical Causal Models tend to focus on graphical representations and mathematical formulation, relying less on textual reasoning. While they may include documentation or annotations, the narrative component is not structurally integrated into the modelling process.

In this regard, the proposed model leverages the narrative clarity of Theory-Based approaches while applying it to a more rigorously structured and layered causal architecture, thus bridging visual formalism and textual interpretability to support both analytical rigour and communicative transparency.

9.2.3. Concluding Remarks

The comparative analysis presented in this chapter offers a structured reflection on how the proposed model aligns with, diverges from, and ultimately advances existing methodological paradigms for sustainability assessment. By systematically examining its core characteristics, such as the multilayered architecture, the focus on deterministic causality, the atomic variable representation, and the centrality of KPIs, the model is shown to embody a hybrid logic that draws selectively from different traditions while addressing their key limitations.

What emerges is a framework that is at once rigorous and operational, capable of offering clarity without oversimplification and quantifiability without losing sight of systemic complexity. In particular, the model stands out for its ability to integrate the structural discipline that participatory models miss with the impact traceability that theory-based approaches tend to dilute and the evaluative granularity that is generally absent from causal or statistical representations.

While many of its individual features find precedent in existing methodologies, it is their systematic combination and formalization that defines the framework’s originality. Thanks to this hybridization process, in fact, the model not only enhances its methodological soundness but also affirms its practical relevance, becoming suitable for real-world applications where accountability, clarity, and comparability are essential. By providing a visually interpretable, logically coherent, and analytically grounded tool, the model contributes to bridging the long-standing gap between sustainability theory and business reporting practice, offering also a solid foundation for future extensions and adaptations across industries and regulatory contexts.

	THEORY-BASED MODELS	SYSTEM DYNAMICS & PARTICIPATORY MODELS	STRUCTURAL & STATISTICAL CAUSAL MODELS	EVALUATION & PRIORITIZATION FRAMEWORKS
Multilayer Sequential Structure	Simpler but sequential	Cyclical and distributed	No fixed stratification	Limited sequentiality
Deterministic Causality	Explicit but aggregated	Fluid and reciprocal	Deterministic and testable	Not inherently causal
One-to-Many Relationships	Implied at category level	Multiple and reinforcing	Analytically central	Lack of individuality
Uniqueness of Variables	Often but not always	Frequent duplication	Dependent on type	Functional to consistency
Atomic Nodes Representation	Only for versions of ToC	Atomic and abstract	Atomic and testable	Possible but not necessary
Signs and Variations	Assumed positivity	On links, not normative	In analysis, not visible	No sign handling
Quantification through KPIs	Optional, loosely linked	Qualitative by default	For validation	Central for priority setting
Impact Categorization	Narrative or time-based	Immediate, mediated, distal	No differentiation	Post-mapping
Cycles Description	Integral to ToC diagrams	Minimal or absent	Rare or absent	Retrospective and extrnal

Table 26: Model’s Elements Comparison with Classified Families

9.3. The SWM Research Landscape

9.3.1. Introduction

Following the model's qualitative application to the Smart Water Management (SWM) project and its methodological validation through comparison with established theoretical frameworks, this section shifts the focus toward a broader academic contextualization. The goal is to assess how the proposed model integrates into, complements, and advances the existing research landscape precisely related to sustainability assessment in the water sector, particularly within digitalized, smart environments.

Over the past decade, a growing body of literature has explored the intersection between digital technologies and sustainable water resource management, including models and frameworks ranging from classic indicator-based dashboards to sophisticated tools grounded in system dynamics, life cycle assessment (LCA), and multi-criteria decision analysis (MCDA). However, despite this diversity and the admirable growing attention to the topic, several limitations persist across the literature and in line with what already highlighted in the former section of literature review. Among the many, a prevailing emphasis on environmental outcomes over social and governance impacts, a reliance on descriptive or simulation-based assessments rather than formal causal modelling, and a general lack of structured frameworks that link digital enablers to long-term sustainability outcomes in a modular and transferable manner. The model proposed in this thesis, characterized by a multilayer causal architecture, KPI-based quantification, and ESG alignment, was designed specifically to address these gaps.

This section aims therefore to position the developed model within the current state of academic research that revolves around the topics of water management and digitalization, highlighting both points of continuity and innovation. Through a structured literature mapping, it will review commonly adopted assessment frameworks in the SWM domain, analyse how different sustainability dimensions are integrated (or overlooked), examine the presence of causal mechanisms in prior work, and compare structurally similar approaches. The final objective is to demonstrate how the model contributes to filling recognized research gaps and offers a coherent, scalable methodology for understanding the complex relationship between digital innovation and sustainability in the water sector, which is till nowadays partly unexplored.

9.3.2. Overview of Existing Evaluation Frameworks in SWM

Recent academic literature on Smart Water Management (SWM) has proposed a wide range of frameworks to evaluate the sustainability implications of digital solutions in

the water sector, highlighting the growing attention that the topic has gained in the last few years. These frameworks vary in depth, methodology, and dimensional coverage, but they can be broadly classified into several main families: KPI-based systems, Life Cycle and Sustainability Assessment models (LCA/LCSA), Multi-Criteria Decision Analysis (MCDA), and System Dynamics Modeling (SDM).

A dominant and operationally appealing method remains the use of Key Performance Indicators (KPIs), which are typically and easily deployed in water utilities or urban programs to track performance outcomes such as leak reduction, energy use, or service continuity. For instance, Dasallas et al. [186] developed a structured KPI-based tool for “Smart Water Cities,” evaluating smart technology implementations across urban water supply, treatment, and disaster resilience domains. However, while their model effectively highlights the role of technological components, such as IoT-enabled monitoring and ICT-based control, in improving urban water systems, it primarily adopts a descriptive lens and focuses on physical performance indicators. Furthermore, authors criticize widely recognized urban sustainability standards, including ISO 37120 and U4SSC, for their limited integration of digital innovation metrics, as they tend to prioritize basic service coverage and conventional environmental indicators and underrepresent key dimensions such as digital governance, institutional responsiveness, and climate resilience [186, 213].

To address such gaps, other studies have adopted Life Cycle Sustainability Assessment (LCSA), as in the case of Souza et al. [208] who applied this method to evaluate decentralized water reuse systems by integrating environmental, social, and economic dimensions. Their results suggest that digital monitoring not only lowers environmental burden but also generates measurable social and financial benefits. However, these LCA/LCSA models typically assess discrete infrastructure options rather than ongoing digital transformations across a utility network, and while they advance the triple bottom line view, they often lack operational traceability between digital enablers and impact-level KPIs.

Multi Criteria Decision Analysis frameworks represent another approach, particularly when linked with scenario simulation and when the goal is to balance multiple sustainability objectives such as water quality, cost, equity, and resilience. It is this the case, for example, of the work by Ramos et al., reviewed by Lassiter-Leonard et al. [213], that integrates MCDA with climate adaptation scenarios, enabling decision-makers to compare trade-offs under uncertainty. Unfortunately, MCDA approaches usually rely on expert-based weighting and often abstract from the granular architecture of smart technologies, omitting the internal dynamics of digital systems and the real-time nature of operational levers.

More dynamically driven, System Dynamics Modeling (SDM) is increasingly applied in the water domain, with examples such as Momeni et al. [206] proposing a coupled SD and optimization framework to simulate the long-term implications of smart leak

detection programs by mapping feedback loops among water supply reliability, costs, and system stress. SDM provides a promising method to represent indirect and nonlinear effects, especially when digital interventions may cause rebound phenomena or emergent behaviours. However, as noted in state-of-the-art reviews [208], most SD applications lack modularity and ESG alignment, and typically focus on environmental impacts over social or institutional performance.

A separate yet growing area is that of layered digital architectures, such as those proposed by Li et al. [203] and Huang et al. [202] that define multi-level technological stacks, ranging from sensing to analytics and decision support. However, while they excel in describing how digital infrastructure is organized, they often lack evaluative layers that track how these inputs produce societal or environmental change. Li et al.'s five-layer architecture, for instance, ends with a "value layer" but does not formalize the links between system capabilities and ESG indicators, and the same holds for Grigg [210], who articulates a smart utility transformation map without explicitly connecting it to sustainable development outcomes.

In contrast, the model presented in this thesis seeks to overcome these limitations, integrating the systemic depth of SDM with the structural clarity of layered architectures, while preserving the quantifiability of KPI frameworks and the evaluative richness of LCSA. Its modular design and explicit causal progressions enable it to serve as both a performance evaluation tool and a research hypothesis engine, addressing the current literature's gaps and the lack of integrated, adaptable frameworks that can represent the full chain from digital implementation to measurable sustainability performance across environmental, social, and governance pillars.

9.3.3. Sustainability Dimensions in Literature

The integration of sustainability dimensions within Smart Water Management (SWM) assessment frameworks has significantly evolved in recent years, but imbalances persist in how different pillars—Environmental, Social, and Governance (ESG)—are represented. Indeed, as already highlighted when dealing with sustainability assessment in broader terms, also in this more specific case a comprehensive review of the literature reveals a strong emphasis on environmental indicators at the expense of the less explored or operationalized social and governance aspects.

As a matter of fact, environmental outcomes remain the most systematically and frequently addressed in SWM studies, with key indicators including reductions in non-revenue water, energy consumption, pollutant loads, and greenhouse gas emissions. For instance, Huang et al. [202] emphasize the role of real-time monitoring, pressure optimization, and smart infrastructure in driving water savings and reducing environmental footprints across urban water grids, while Momeni et al. [206] use

system dynamics to show how digital leak detection and demand forecasting contribute to long-term environmental and economic resilience. This dominance is partly due to the greater quantifiability and direct connection that these indicators have to regulatory targets or utility performance benchmarks, as environmental KPIs are not only more readily measurable through existing monitoring systems but also often mandated by national or regional regulations. Moreover, they align closely with traditional engineering performance objectives, making them easier to incorporate into technical assessments and investment planning, being therefore prioritized in both academic evaluations and reporting frameworks.

Economic considerations, often linked to operational efficiency, are also well integrated, as studies frequently report on cost savings, return on investment, or improved asset utilization resulting from the deployment of digital water technologies. In this regard, studies have for instance focused on the ability of digital twins to optimize pump schedules and reduce maintenance costs while simultaneously enhancing energy efficiency and water availability [202, 210].

In contrast, social and governance dimensions are far less consistently represented and, while some studies include indicators such as customer satisfaction, accessibility, or awareness (e.g., through smart meter feedback), these are often evaluated qualitatively or treated as secondary outcomes. Dasallas et al. [186] note that traditional smart city KPIs often marginalize issues of digital inclusion, equity of access, or participatory governance, which are instead central when considering the broader effects of digitalization projects on society. Similarly, also Lassiter-Leonard et al. [213] highlight that many municipal SWM initiatives underrepresent community engagement, behavioural change, and institutional transparency in their assessment schemes.

Reassuringly, more recent efforts are beginning to correct this imbalance, with Huang et al. [202] proposing the inclusion of participatory platforms, mobile citizen reporting apps, and data-sharing policies as key components of smart governance in water systems and Zhang and Cao [207] putting effort to empirically show that digital infrastructure alone is insufficient to improve natural resource efficiency unless combined with government digital capacity and institutional readiness. Their findings support the notion that organizational practices and governance models are essential mediators in achieving sustainability outcomes and pave the way to the awareness that sustainability dimensions are always interconnected.

From a normative and policy perspective, the rise of SDG-driven evaluations has encouraged broader framing and the increasing linkage of SWM to SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and SDG 11 (Sustainable Cities), especially in works aiming to integrate digital transformation with urban resilience and equity goals [213, 215]. Nonetheless, the actual

operationalization of SDG-aligned indicators remains patchy, often limited to general associations rather than rigorously mapped causal linkages [216].

In this fragmented landscape, the developed model offers the critical innovation of embedding ESG and SDG alignment into the model's structure from the outset. Moreover, linking digital inputs to intermediate levers and downstream indicators, it ensures that social well-being and governance quality are not afterthoughts, but systematically evaluated through quantifiable variables. Indicators such as service continuity, transparency, and stakeholder inclusion are in fact treated as primary outputs, thereby addressing one of the most persistent gaps in SWM sustainability assessment research.

9.3.4. Structural Comparison with Similar Models

The model proposed in this thesis, characterized by a modular, tiered architecture linking digital enablers to sustainability outcomes, finds structural resonance with several frameworks in the recent literature, but it also introduces conceptual and methodological advancements that distinguish it within the Smart Water Management (SWM) research field. In particular, the model goes beyond traditional layered technology descriptions by embedding a causal logic, quantitative KPI anchoring, and ESG/SDG alignment, thus transforming conceptual architectures into testable and policy-relevant tools.

A clear structural precedent is found in the five-layer architecture developed by Li et al. [203], which delineates the Smart Water System (SWS) into technical layers ranging from sensor infrastructure to application-level benefits. This model provides a valuable framework for organizing digital components, but it lacks an explicit mechanism for evaluating the effects of these components on sustainability metrics. Similarly, Huang et al. [202] propose a vertically integrated model for smart water systems that encompasses data sensing, transmission, analytics, and decision support, and which is designed to reflect real-world ICT stacks. While both models offer strong foundations for system design and integration, they remain descriptive and technology-centric, with limited attention to sustainability performance or causal pathways.

The model developed in this thesis builds upon and extends these architectures by explicitly embedding directional cause-effect relationships between layers, with the result that the logic advocated in systems thinking is mirrored but made more concrete and traceable through defined variables and measurement strategies.

As partly highlighted in the previous chapter, another relevant lineage can be found in logic models and theory-of-change frameworks, especially those used in policy and development contexts. For instance, projects such as iWIDGET and others in EU-funded water research have used such frameworks to map how digital inputs (e.g.

smart meters, analytics tools) translate into behavioural, operational, and environmental outcomes [213, 214]. Once again, however, while these models recognize the mediating role of digital practices and information flows, they often stop at high-level logic diagrams and are rarely formalized into scalable or data-ready tools. The proposed SWM model can be then seen as a detailed implementation of this philosophy, offering a modular, quantifiable theory-of-change for the water sector.

The system dynamics literature also contributes structurally similar frameworks, with the already mentioned Momeni et al. [206] using causal loop diagrams and feedback simulations to examine long-term system behaviour under digital and policy interventions. Unfortunately, while powerful for exploring emergent effects and system resilience, SD models often lack a granular representation of digital architectures and do not isolate technology-specific levers within a layer-based structure. Furthermore, many SD applications still focus disproportionately on environmental variables, underrepresenting social and governance dimensions [216, 217].

Lastly, a final connection with current literature can be recognized in the most recent digital transformation models for water utilities, used to suggest layered transitions from physical systems to analytics and strategic decision-making [210]. However, these remain narrative frameworks, useful for conceptualizing evolution paths but lacking the evaluative structure necessary for performance benchmarking or policy analysis, which is instead a central focus of the originally developed model, that integrates KPIs at each level and ties them to broader ESG outcomes.

In summary, while several models in the literature resemble the thesis framework in terms of layering or modularity, they tend to fall short in either lack of causal formalization, absence of quantitative metrics, or insufficient linkage to sustainability frameworks. The proposed model synthesizes these dimensions, offering a novel structure that is both analytically rigorous and application-ready, able to align with the evolving research direction that calls for models capable of capturing the complex, multi-stage, and interdisciplinary nature of digital water transitions.

9.3.5. Contribution to Advancing the Research Landscape

Building on the comparative insights presented thus far, it becomes clear that the proposed Smart Water Management (SWM) assessment model makes a substantive contribution to current academic and applied research. Indeed, while inspired by and structurally aligned with existing models in digital water and sustainability domains, it introduces a number of integrative and innovative elements that directly address a consistent series of long-standing gaps in the literature, some of which already outlined.

Among the model's most significant contributions is the ability to bridge the historically fragmented perspectives that characterize SWM evaluations [202]. In fact, while engineers have focused on technical performance, economists on cost-efficiency, and environmental scientists on ecological outcomes, few frameworks have succeeded in integrating these layers into a unified, causally coherent structure, and the proposed model figures among them [202, 213]. It bridges this siloed context by mapping the full trajectory from digital input to sustainability impact, thereby enabling a system-level perspective and ensuring that improvements at the technical layer, such as smarter leak detection or better forecasting, are traced through intermediate processes to final outcomes [206]. In academic terms, the model is a practical implementation of the socio-technical systems perspective, treating technology, human decision-making, and sustainability targets as interconnected [215].

By explicitly distinguishing controllable factors from resulting indicators, the developed model also aids in attribution, which has been a perennial challenge in impact assessment due to the existence of so many confounding factors that make it hard to prove the direct causality between an input and a generic effect [207]. By distinguishing controllable inputs (e.g., sensor quality, analytics capabilities) from dependent indicators, the model makes it possible to test hypotheses across layers and consequently understand to what extent the introduction of a specific device is expected to affect one or more organizational metrics [204, 209]. This type of attention for causality and formal chains is rarely operationalized in existing KPI dashboards or MCDA frameworks, which tend to aggregate outcomes without explaining them [206, 213].

Another significant contribution lies in the model's emphasis on modularity and the recognition that each layer corresponds to an active research domain, ranging from IoT deployment and data analytics to operational optimization and sustainability monitoring. This structural alignment makes the model inherently compatible with ongoing empirical findings, such as those emerging from recent studies on AI for smart irrigation [205] or system dynamics in water resource management [206], and allows new insights from applied research to be seamlessly mapped onto the framework with their downstream effects captured through operational and sustainability KPIs. In this sense, the model acts as a living evidence repository, enabling both researchers and decision-makers to incorporate, test, and communicate findings in a structured and cumulative way [202].

Furthermore, this modularity not only enhances the model's adaptability but makes it well-suited for guideline development and standardization, serving as a scientific backbone for clarifying not just which technologies to adopt, but why they matter and how they lead to measurable outcomes. In this regard, given the fragmented and often inconsistent normative landscape, frequently cited as a major challenge by both scholars and practitioners, it is no coincidence that authors such as Dasallas et al. [186]

have called for the development of unified, KPI-based certification schemes to guide the implementation of smart water cities.

Unlike most existing frameworks, which often treat ESG or SDG alignment as peripheral or post hoc considerations [215], the proposed model embeds these dimensions at its core, explicitly mapping final outputs to ESG and SDG indicators and integrating this aspect from the very beginning of the analytical process [202, 186]. For instance, improvements in leakage detection rates and network efficiency are not only tracked as operational KPIs, but are also interpreted as direct contributions to SDG 6.4 (water use efficiency) and SDG 9 (infrastructure resilience) [207]. These improvements further align with the environmental metrics increasingly used in corporate ESG reporting frameworks, enhancing the model's relevance for public accountability and sustainability disclosure [186, 215], and creating a shared interpretive framework that enables alignment between technical performance and strategic sustainability objectives, fostering a common language for engineers, policymakers, and sustainability officers alike. Fundamentally, the inclusion of ESG and SDG logic within the structure of the model allows to anticipate and respond to the maturing demands of sustainability science, where cross-scale coherence and outcome accountability are increasingly emphasized [213, 216].

A persistent concern within the Smart Water Management (SWM) literature is the lack of cumulative, coherent evidence regarding the real-world sustainability impacts of digital technologies. Indeed, while numerous studies have showcased promising pilot projects or described technical innovations, such as smart meters, AI-driven leak detection, or digital twins, the field as a whole remains fragmented, with most frameworks either limited to specific case studies [204, 209], focused narrowly on operational performance [186], or presenting simulation-based insights without structured mechanisms for validating long-term sustainability outcomes [206, 213]. The proposed model directly addresses these challenges by offering a causally structured and modular framework that enables standardized measurement across digital and sustainability variables, while also providing researchers and practitioners with a platform to formulate hypotheses, guide data collection across distinct layers—and assess the replicability of results across different contexts [202, 206]. In doing so, the model lays the groundwork for comparative and longitudinal research designs, advancing a more robust and methodologically consistent body of evidence in the SWM field.

9.3.6. Concluding Remarks

In a context where sustainability assessments in Smart Water Management (SWM) remain fragmented and methodologically uneven, what ultimately sets the model apart is not merely its methodological rigor, but its ability to synthesize and

operationalize the most effective aspects of the current literature into a single, integrated structure. It builds on layered digital architectures [203], draws from system dynamics modelling to account for temporal and feedback effects [6,18], incorporates quantitative KPI logic for comparability [186], and hardwires ESG/SDG alignment for policy coherence [202, 207, 215]. Yet it moves beyond these individual contributions by explicitly linking them into a functional and testable causal chain, applicable across diverse smart water contexts.

In doing so, the model moves beyond theoretical contribution to serve as a practically deployable tool that helps ensure digital transformation efforts in the water sector result in measurable, multidimensional sustainability outcomes. It enables researchers to connect local innovations with global development goals and supports practitioners in navigating a complex ecosystem of digital systems, regulatory demands, and stakeholder expectations.

Its capacity to act as a living, evidence-based repository makes it particularly valuable in a research landscape that increasingly demands methodological transparency, empirical grounding, and policy relevance. By providing a common logic that links technologies, operations, and sustainability impacts, the model helps close the persistent gap between digital ambition and accountable progress in smart water transitions. It ultimately contributes to building a more coherent and cumulative research agenda in which evidence can be meaningfully accumulated, compared, and used to inform both academic advancement and real-world decision-making.

10 Conclusions

10.1. Introduction

Building upon the analysis of current academic and institutional approaches, the development of a structured KPI framework, and the design and application of a causal model for assessing digital solutions' impact on sustainability, this chapter aims to synthesize the main findings, underline their theoretical and practical implications, and acknowledge the study's boundaries.

In a context where sustainability reporting is becoming both a regulatory requirement and a strategic priority, and where digital transformation offers new opportunities and challenges, the research sought to provide clarity, structure, and guidance to organizations navigating this complexity. Aware of the gap between sustainability ambitions and measurable outcomes, this study tried to answer to the most recurrent questions in terms of reporting practices and impact evaluation, developing flexible yet rigorous tools that provide a structured basis for sustainability assessments, ensure alignment with regulatory frameworks, and evaluate the contribution of digital technologies through a transparent, evidence-based model.

The following sections will therefore summarize the key results, discuss their value for academia and practice, highlight the limitations of the research, and propose directions for future investigation, all in line with the ultimate goal of advancing the analysis of corporate sustainability, with consequent benefits for both companies and researchers.

10.2. Summary of Key Findings

The research carried out in this thesis was developed with the goal to answer three core challenges discovered at the intersection of sustainability assessment and digital transformation:

1. the lack of consistent, structured, and methodologically grounded reporting practices that can guide organizations in selecting, measuring, and communicating sustainability performance in a clear and comparable way;
2. the difficulty of both establishing robust causal links between digital initiatives and sustainability outcomes and understanding whether their overall impact,

which includes both positive and unintended negative effects, is ultimately beneficial;

3. the need to ensure that the developed model could be generalized, scaled, and transparently applied across diverse sectors and projects, offering a structured, repeatable process that facilitates its replication and adaptation beyond the original case of development.

To respond to these challenges, the research developed a set of integrated solutions, each corresponding to one of the identified gaps and based on either literature analysis, framework design, model development, or empirical validation.

Construction of an ESG Framework for Structured Reporting Practices

The first key challenge identified through the literature review was the absence of a coherent, standardized, and methodologically sound approach to sustainability reporting, due to the major inconsistencies between existing directives and the lack of a universally accepted framework. Indeed, despite the proliferation of ESG agendas and voluntary disclosure initiatives, organizations continue to face uncertainty in selecting relevant KPIs for drafting their reports, especially when trying to balance regulatory expectations, stakeholder demands, and internal strategic priorities. This ambiguity is further exacerbated by the excessive focus on environmental indicators, which often leaves the social and governance dimensions underrepresented, fragmented, or qualitatively assessed, thereby limiting comparability and undermining the credibility of corporate sustainability reports.

To respond to this gap, the study developed a comprehensive and hierarchically structured ESG framework, providing a solid basis for more complete, rigorous, and customizable sustainability assessments. Constructed in line with the model originally developed by the Digital & Sustainable Observatory of Politecnico di Milano [218], the framework was populated through a multilayered process that led to the inclusion of over 200 KPIs systematically collected from academic literature, regulatory documentation, standardized templates, and exemplary sustainability reports published by internationally recognized companies. The selected indicators were then categorized by ESG dimension, further broken down into thematic second-, third-, and fourth-level subcategories, introduced to enable a more schematic and immediate understanding of the template especially when dealing with majorly populated classes. In this regard, particular attention was given to ensuring that no subcategory remained empty or disproportionately populated, thereby supporting a balanced representation of all sustainability areas. To improve transparency and operational usability, which was a primary objective of the research, each KPI was clearly defined and associated with a specific formula or unit of measurement, drawn from either academic or institutional sources. This methodological step was particularly important in supporting standardization, enabling benchmarking, and fostering comparability

between companies, sectors, and contexts. Moreover, in a context where companies continuously claim difficulties in quantifying sustainability and integrating it into their disclosures in measurable terms, the resolution of specifying each formula and measurement scale proved essential to offer organizations concrete, ready-to-use tools to transform abstract principles into actionable metrics. As direct consequence, the framework also becomes an instrument to track progress over time, communicate results credibly to stakeholders, and align with emerging regulatory expectations that increasingly demand data-driven evidence of sustainability performance.

While fashion, food, and ICT. As extensively explained in the chapter, these industries were selected based on their economic significance, sustainability complexity, and representativeness the majority of KPIs were framed in general and cross-sectoral terms to ensure maximum flexibility and transferability, the framework also incorporates a small selection of more context-specific indicators drawn from the three strategically chosen sectors of national and international ESG challenges, prioritized either due to their high material intensity, environmental footprint, digitally related responsibilities, or visibility in the current landscape. Sources belonging to these sectors were chosen not only for the quality and transparency of their reporting practices, but also for the depth and methodological rigor of their ESG frameworks, whose contribution was particularly valuable in filling persistent gaps in the social and governance pillars.

Importantly, it must be emphasized that the framework was developed not to offer an exhaustive inventory of all existing sustainability indicators but, rather, to provide a curated and practical selection of KPIs that companies may consider when building or revising their reporting systems. By doing so, it is intended to serve a dual function:

- A reference toolkit for organizations seeking to navigate complex ESG disclosure requirements
- A guiding structure for ensuring completeness and consistency, especially in capturing nuanced or underrepresented dimensions of sustainability.

This completeness is essential, as many companies, especially small to medium-sized ones, are recognized to report selectively, often overlooking critical impact areas due to lack of awareness, expertise, or operational tools. By offering a modular, transparent, and methodologically grounded system, the framework helps companies avoid this pitfall, equipping them with the resources needed to conduct more reliable and holistic evaluations of their ESG performance.

Development of a Causal Model for the Net Impact Assessment of Digital Solutions

The second major challenge identified through the research concerns the lack of clear, evidence-based methods for evaluating the relationship between digital transformation and sustainability performance. While digital technologies are often

described as enablers of ESG advancement thanks to qualities such as automation, real-time monitoring, data integration, or efficiency gains, academic literature and practitioner insights consistently point to a fundamental gap: the absence of structured methodologies that can trace, quantify, and validate the causal links between technological initiatives and sustainability outcomes.

On one side, organizations struggle to demonstrate how specific digital solutions affect environmental, social, or governance dimensions, while, on the other, there is an increasing awareness that digitalization can produce not only positive but also negative effects, mainly due to the introduced risks related to increased energy consumption, cybersecurity vulnerabilities, or unintended workforce disruptions. Without a robust model to evaluate this trade-off, companies risk either to embrace digital innovation without fully understanding or managing its implications on sustainability or to deliberately avoid undertaking technological solutions because afraid of their hidden consequences and drawbacks. A clear illustration of all advantages and cons related to digital solutions would not only ensure a more informed organizational behaviour but would also enable a more accurate evaluation of alternative options when planning new projects or restructuring internal processes.

To respond to this issue, therefore, the study developed a multilayer causal model capable of tracing the contribution of digital technologies to sustainability results across the three ESG dimensions. Structured around a tiered logic, the model is composed of eight distinct levels and five typologies of variables, starting with implemented technologies and then moving to digital levers, operational outputs, impacted drivers, and, finally, sustainability KPIs, all framed within the corresponding ESG dimensions. With a strong causal architecture, the model does not merely describe correlations but articulates the functional and organizational mechanisms through which technologies influence ESG variables, ultimately allowing practitioners to identify not just what is changing, but how and why.

Its core and innovative element is, however, the focus on drawing causal paths, that are mainly forward but potentially also backward traceable, with the goal of accurately linking each observed impact to the digital and operational enablers that triggered it, and vice versa. This structure allows for a deep understanding of the systemic interdependencies that underlie sustainability outcomes, offering organizations the ability to assess not only the effects of a given digital intervention but also to backtrack from a specific ESG goal to the enabling conditions required to achieve it. By uncovering these bidirectional relationships, the model becomes a strategic tool for guiding decision-making, prioritizing investments, and anticipating unintended consequences. In this way, moreover, it moves beyond conventional evaluation models, providing a rigorous, transparent, and actionable approach to measuring the net sustainability impact of digital transformation initiatives. Interestingly, in fact, the model doesn't automatically equate digitalization to sustainability, but instead allows to draw both positive and negative paths leading to final KPIs that, once summed and

evaluated according to their relevance in terms of certainty and strategic alignment, provide a more realistic and balanced picture of the overall impact. This approach enables organizations to recognize trade-offs, quantify unintended consequences, and avoid overestimating the benefits of digital initiatives without accounting for potential drawbacks.

Validated through the application to the Smart Water Management Project by Al maviva, the model proved to be an extremely valuable tool for assessing the net effect across all ESG pillars and supporting more responsible, evidence-based decision-making, where digital transformation is guided by measurable sustainability outcomes rather than assumed benefits. Results highlighted that the implementation of digital technologies such as IoT sensors, remote diagnostics, and decision-support systems, all installed for facilitating remote access control of the water network, led to significant positive impacts, particularly in terms of environmental and operational efficiency. Despite the initial focus on resource saving and climate protection, the project showed significant positive effects on the social and governance sides as well, with the model quantifying improvements in technician safety and risk exposure, monitoring accountability, reduced error margins, and greater transparency in reporting. Obviously, and in line with what previously mentioned, also marginal negative impacts got identified, ultimately offering a holistic, net-positive assessment of the project's sustainability impact.

Formalization of a Scalable and Transferable Methodology

To properly serve all the researchers and companies that currently struggle with sustainability assessment, a key objective of this study was to ensure that the proposed causal model could also achieve a high degree of generalizability, scalability, and transparency. Rather than remaining confined to the specific case for which it was originally developed, the model was designed from the outset with the goal to become a flexible framework, capable of being applied, adapted, and extended across different sectors, technologies, and organizational settings.

Effort was therefore put into codify, formalize, and generalize the proposed causal model, transforming what began as a tailored solution for the Smart Water Management project, which served as solid and tangible basis for the development process, into a scalable and reusable methodology. The intent was to preserve the conceptual depth and internal coherence of the model while transforming it into a clear sequence of steps that researchers, professionals, and institutions could apply across different projects, sectors, and organizational structures, without needing to reconstruct the framework from the ground up. Indeed, what originally required significant time, analytical refinement, and experimentation was thus translated into a clear, structured, and replicable pathway that retains analytical rigor while offering accessibility and clarity.

To this end, a dedicated application procedure was developed, outlining a five-step guide that users can follow to reconstruct and apply the model in their own projects. This supporting methodology was not conceived as a rigid checklist, but rather as a facilitative roadmap, designed to clarify the model's logic, reduce ambiguity, and enhance replicability across different contexts. It indeed synthesizes the core analytical operations that underlie the model's construction, including for instance the identification of technologies, the mapping of functional and operational changes, and the selection of relevant KPIs, while however remaining adaptable to the user's specific goals and available data.

By offering a formalized yet flexible method for implementation, the research enables future users to replicate the causal reasoning embedded in the model, while tailoring the content to the particular characteristics of their case. In doing so, the framework becomes not only a static outcome but a dynamic resource, reliable in its structure, responsive to different needs, and reusable across sectors. This formalization ultimately strengthens the model's practical relevance, increases its scientific transparency, and ensures that its value extends well beyond its original application.

10.3. Theoretical and Practical Contributions

Starting from a detailed analysis of existing literature and institutional practices, the research presented in this thesis offers significant contributions both at the theoretical and practical level, and builds a solid conceptual foundation for understanding the complexity of sustainability assessment in the digital age. Through the development of a comprehensive ESG framework and a multilayer causal model, the study bridges methodological gaps, introduces new tools for performance evaluation, and proposes a formalized approach to measuring the sustainability impact of digital transformation.

Notably, both the framework and the model were not designed to analyse a specific organization, but rather to serve the broader purpose of enabling structured and generalizable assessments of sustainability performance across multiple industries. Indeed, while the Smart Water Management project developed by Almaviva served as a concrete and valuable testing ground, the primary objective of the research was not to study Almaviva per se, but to provide a transferable methodology for analysing similar digital initiatives implemented by any organization, in any sector.

10.3.1. Value for Academics

From a theoretical and methodological standpoint, this research offers several important contributions to the academic discourse at the intersection of sustainability assessment and digital transformation.

First, it provides a comprehensive and structured literature review that maps 83 academic papers and institutional sources to outline the evolution, diversity, and fragmentation of current sustainability assessment approaches. This review highlights not only the conceptual variety in the field, but also recurring challenges such as the lack of integrated models, the uneven treatment of ESG dimensions (with a strong dominance of environmental metrics), and the general absence of rigorous causal reasoning in the analysis of digital impacts. In doing so, the review clarifies existing gaps in the academic landscape and provides a robust foundation for future theoretical development.

Second, the study contributes by systematically classifying 12 modelling approaches across four main methodological families, respectively named Theory-Based Models, Systemic and Participatory Models, Structural and Statistical Models, and Evaluation and Prioritization Frameworks. This partly original and partly literature-supported categorization enables a more nuanced understanding of each model's assumptions, logic, and applicability, helping scholars to critically compare and position new research within an established methodological landscape. Enriched by a series of analytical dimensions, such as purpose, causal orientation, granularity, data dependence, and degree of formalization, the performed classification allows for a structured evaluation of each model's strengths and limitations that holds value beyond the boundaries of this specific study. Deduced from this thesis context, it can serve as a practical reference for researchers who find themselves in the position of choosing among alternative modelling approaches for their own work, as it clearly and carefully discloses all models' characteristics and structural elements. The systematic overview and comparative synthesis allow future scholars to assess the suitability and alignment of each model with their research objectives, data availability, and analytical needs, facilitating more informed methodological decisions and encouraging greater coherence.

Among its direct and original outputs, the thesis provides an academically grounded yet operationally oriented contribution through the development of a structured ESG framework that, basing on a hierarchical classification system, offers a new lens through which to organize and interpret sustainability performance across environmental, social, and governance dimensions. conceived with potential applications in corporate auditing and reporting, the framework primarily holds academic value, serving as a structured and analytically grounded tool for organizing ESG indicators, enabling comparative research, supporting indicator standardization, and deepening theoretical reflections on sustainability measurement practices across

sectors. By addressing long-acknowledged limitations in the treatment of social and governance indicators, and by collecting and integrating over 200 KPIs from different sources, the framework enriches existing theoretical constructs and supports more holistic sustainability evaluations. In particular, the clarity of definitions, the alignment with major international standards, and the flexibility to adapt across contexts make it a valuable reference for future empirical studies, comparative assessments, or theoretical explorations into indicator selection, disclosure behaviour, or performance benchmarking.

Then, building on the previously illustrated analytical groundwork, the thesis introduces a hybrid multilayer causal model that extends existing theoretical approaches in both scope and function, defining itself as an academically solid but de facto original methodology. While grounded in principles drawn from the literature, such as logic modelling, system thinking, and causal inference, it proposes a novel architecture that connects technological inputs to ESG outcomes through an articulated sequence of intermediate levers and operational changes. In this way, it brings conceptual clarity to the ambiguous space between digital transformation and sustainability performance, offering a new lens for analysing how digital tools actually generate impact.

A key academic value of the model lies in its formalization as a methodological resource since, rather than remaining a context-bound artifact, it was codified into a generalizable and transferable method, enabling other researchers to apply, replicate, or extend it in different settings. By providing both the structural logic and the application procedure, the study helps foster methodological transparency, academic replicability, and theoretical consistency, ultimately contributing to the cumulative logic of research and addressing the issue of isolated case studies that cannot be easily compared or built upon.

Moreover, thanks to the possibility to maintain the structure while adapting the variables to reflect different technological configurations and organizational contexts, the model provides a framework through which scholars can compare sustainability outcomes in projects with similar digital components but different implementations. This flexibility enhances its academic utility for cross-case research, longitudinal studies, or meta-analytical reviews of digital sustainability initiatives.

Finally, the model explicitly encourages a causal reasoning mindset, which remains underdeveloped in much of the literature on ESG and digital transformation. By encouraging scholars to think in terms of enabling technologies, intermediate mechanisms, and observable impacts, it contributes to more rigorous theorizing and to the development of testable hypotheses for future empirical work. In doing so, it supports not only theory-building but also empirical validation, opening the door to further quantitative, qualitative, or mixed-method applications in diverse research contexts.

In sum, the academic value of this work lies in its ability to bridge conceptual fragmentation, contribute methodological innovation, and offer a reusable and extensible platform for the growing field of sustainability-oriented digital transformation research.

10.3.2. Value for Practitioners

From a practical standpoint, the outputs of this research respond directly to some of the most urgent and recurring needs expressed by organizations dealing with the soon compulsory topic of sustainability assessment and the relentless advancement of digital transformation. Indeed, in a context marked by increasing regulatory pressure, stakeholder scrutiny, and internal demand for strategic clarity, companies often struggle to structure their ESG reporting, track the impact of digital investments, and translate complex sustainability goals into actionable and measurable outcomes. To address these challenges, the present study came to rescue by developing two major tools, an ESG framework and a multilayer causal model, aimed at supporting a more rigorous, data-driven, and transparent approach to sustainability management.

The first major output, the structured ESG framework, provides a practical and user-oriented tool that companies can adopt to design or improve their sustainability reporting systems. Organized around environmental, social, and governance dimensions, and structured through multiple levels of subcategorization, it offers a curated selection of over 200 KPIs, each accompanied by specific formulas or measurement criteria. This structure supports companies in identifying reporting gaps, aligning with international standards, and ensuring a balanced representation of all ESG dimensions, with particular regard to the social and governance areas, which were recognized to be often neglected in conventional reporting.

Going beyond its role as a reference for completeness, the framework can be actually used as a navigable repository from which companies can easily select the impact areas most relevant to their sector or strategy and, thereafter, the KPIs that best reflect their priorities, constraints, and stakeholders' expectations. The framework, in fact, was purposely designed to allow this kind of flexible consultation, being usable as-is or enriched with new indicators tailored to the specific features of an industry, geographic context, or business model. In this way, it ensures both consistency and adaptability, supporting organizations in building customized, yet methodologically grounded, sustainability reporting systems.

Fundamentally, while the framework is adjustable to the unique characteristics of each organization, it promotes internal coherence and external comparability, offering a transparent reference point for both voluntary and mandatory disclosure activities.

The second major output, the multilayer causal model, supports companies in going beyond compliance and toward strategic ESG integration, truly understanding the

multitude of implications of developing digital solutions into their business. Indeed, by clearly linking implemented technologies to sustainability outcomes through an articulated sequence of digital levers, operational shifts, and impact variables, the model helps organizations understand how their digital initiatives contribute to environmental, social, and governance performance. This is particularly relevant in an era where digital transformation is often pursued without a clear structure for evaluating its sustainability effects, leading to missed opportunities, misguided investments, or underestimated risks.

When applied to different contexts, users are expected to adapt the content of the model to the specific characteristics of the project under analysis, modifying the enabling technologies, operational levers, or KPIs according to the sustainability goals and organizational environment. Interestingly, however, the research shows that when different projects involve the same technologies, a large part of the activated digital levers is likely to remain consistent, regardless of the sector or organization, as they depend directly on the inherent capabilities of the tools rather than on the context in which they are implemented. This obviously enhances the model's reusability, enabling companies to retain core technological logic while adapting the surrounding variables to their own conditions.

Unlike many existing tools that remain abstract or too narrowly focused, the model is designed to be both methodologically rigorous and practically applicable, enabling companies to trace the full pathway from digital input to ESG outcome, identify potential trade-offs, and build tailored strategies based on their own technological configurations and organizational structures. Through its formalization as a reusable methodology, and the illustration of a simple, practical guide, the model also becomes a replicable asset, one that can be applied to different projects within the same organization or across different entities working with similar technologies.

Importantly, even if graphically designed for moving from the bottom to the top, the model allows for both forward and backward reasoning, enabling organizations to not only assess the sustainability impact of a completed project, but also to plan future initiatives by identifying the technological and operational conditions needed to achieve specific ESG goals. This makes the model a valuable tool not only for sustainability officers and reporting teams, but also for digital strategists, innovation managers, and decision-makers tasked with aligning digital investments to long-term sustainability agendas and improving defecting areas.

Furthermore, by emphasizing net impact and explicitly accounting for both positive and negative effects, such as environmental gains alongside potential increases in energy use or cybersecurity risks, the model fosters a more realistic and responsible approach to digital sustainability. Making all results and implications clearly visible, it empowers companies to avoid greenwashing narratives and instead engage in

credible, evidence-based reporting that can withstand external scrutiny and guide internal improvement.

In sum, the practical value of this research lies in its ability to equip organizations with ready-to-use, adaptable, and transparent tools for managing the intersection of digital transformation and sustainability. Whether the goal is compliance, impact measurement, or strategic foresight, the framework and the model together offer a comprehensive approach to understanding, governing, and communicating ESG performance in the digital age.

10.4. Limitations

While the research presented in this thesis offers original and relevant contributions at both the theoretical and practical level, it is important to acknowledge a set of limitations that may influence the interpretation, applicability, and scalability of its results. These deficiencies, however, do not undermine the validity or usefulness of the proposed framework and model but rather offer a more grounded and transparent view of the conditions under which the results should be interpreted and applied. Acknowledging these boundaries not only strengthens the academic integrity of the study but also provides essential input for those seeking to replicate, extend, or operationalize the tools developed herein.

In particular, the ESG framework and the multilayer causal model, despite being carefully constructed and conceptually sound, inevitably reflect certain methodological assumptions, data constraints, and context-specific conditions that must be considered when evaluating their generalizability and implementation potential. Understanding these factors is crucial for future users, whether academic or professional, who may wish to adapt the outputs to their own use cases or contribute to their further development.

The following paragraphs therefore outline the main limitations associated respectively with the ESG framework and the multilayer causal model developed throughout the thesis, highlighting areas where further refinement or empirical expansion would be most valuable.

10.4.1. ESG Assessment Framework

Despite its methodological clarity and operational usefulness, the framework developed for facilitating and ensuring ESG performance assessment presents some intrinsic limitations, stemming primarily from the interpretative effort required during its construction and from its intended cross-sectoral applicability.

One significant limitation lies in the subjectivity involved in the selection and classification of KPIs, including the subsequent association of respective metrics. Although the process was grounded in academic literature, institutional documents, and the sustainability reports of best-in-class companies, many sources did not provide precise definitions, formulas, or categorization schemes, determining, as a result, the necessity to embrace a qualitative interpretation of the less described ones and those that could logically belong to multiple impact areas. Similarly, since many articles just provided extensive lists of KPIs without offering clear explanations or definitions, formulas and measurement scales were either adapted or constructed from scratch to enhance the model's completeness, but without the possibility of full empirical validation. These choices, while reasonable and documented, inherently introduced an element of subjectivity that could lead to different outcomes if approached differently by other researchers or institutions. Additionally, although the framework includes a broad and carefully curated set of over 200 KPIs, the collection cannot be considered exhaustive, as it was not feasible to review every potentially relevant publication, guideline, or company report related to a continuously evolving landscape such as that of sustainability reporting. It is moreover important to acknowledge that multiple valid approaches often exist for measuring the same impact area, and different organizations may adopt distinct metrics based on their sector, maturity level, or strategic focus. As such, the framework should be interpreted as a comprehensive but non-final or binding repository, more oriented to highlight how to monitor all existing dimensions rather than imposing fixed and obligatory indicators.

Connected to this, another partial concern to acknowledge is the impossibility to practically test or apply some of the indicators included in the framework, particularly those originally developed or re-elaborated to fill the gaps identified in the social and governance dimensions. Indeed, while the majority of the KPIs were drawn from reliable, externally validated sources, a smaller subset of indicators had to be constructed directly by the researcher to ensure the overall completeness and structural balance of the framework, especially in areas where existing documentation was either too generic, qualitative, or entirely absent. These newly created KPIs were formulated in alignment with the conceptual definitions and classification logic of the Digital & Sustainable Observatory, and were carefully designed to include only data points that companies are typically expected to collect or already monitor for other internal or reporting purposes. Nevertheless, these indicators, though logically sound and operationally grounded, have not yet been tested in real-world conditions, nor validated through application in corporate settings and, as such, their practical measurability, consistency across organizations, and overall utility in real reporting scenarios remain to be empirically verified.

A third limitation concerns the framework's sector-agnostic design, which, while intentionally adopted to ensure maximum applicability across diverse organizational contexts, may limit its immediate precision or perceived relevance for companies

operating in highly specialized, heavily regulated, or niche sectors. Unlike many of the sources reviewed during the literature analysis, which tended to focus narrowly on individual industries or application domains, this framework was conceived from the outset as a general-purpose tool, usable by any organization regardless of size, sector, or reporting maturity. This choice reflects the underlying goal of promoting broad accessibility and standardization, particularly for those companies that currently lack internal resources or tailored tools to structure their ESG reporting activities. However, from another perspective, this neutral positioning may be viewed as a potential weakness, as some practitioners might find the framework too generic or insufficiently detailed for addressing their sector-specific sustainability priorities. In these cases, while the framework offers a valuable starting point, it would need to be adapted and enriched with more specialized KPIs to ensure full contextual relevance. The tool was intentionally developed to be usable by as many organizations as possible, which is why, when selecting specific company reports to enrich the list of indicators, the focus was placed on the most prominent and influential sectors in the national landscape, namely food, fashion, and ICT. However, this focused inclusion may be interpreted as favouring certain sectors over others, potentially limiting immediate resonance for smaller companies or organizations in less represented domains. This reinforces the need for users to see the framework as a flexible repository, one that supports adaptation, expansion, and continuous alignment with evolving sectoral needs and priorities.

Lastly, while the framework was developed in close alignment with major ESG directives and the ESRS taxonomy, it is important to acknowledge that it reflects the regulatory landscape and disclosure expectations available at the time of its construction. As such, it should not be seen as a rigid or exhaustive tool, but as a well-grounded starting point that must be used responsibly and kept up to date. Regulatory bodies and standard-setting institutions are continually releasing new guidelines, sector-specific standards, and reporting obligations and it is therefore likely that new areas of interest or additional KPIs will emerge as mandatory in the near future. Obviously, this is not a limitation of the framework itself, which, by design, cannot anticipate future developments, but rather a consideration for future practitioners and organizations. Users are encouraged to apply the framework with awareness of the evolving regulatory context and to review and refine their selected indicators accordingly, at least when mandatory disclosures are released and put into practice.

10.4.2. Multilayer Causal Model

Moving now to the second major output of this work, namely the multilayer causal model developed to connect technological installations to their impacts on sustainability, a few additional limitations can be acknowledged and kept into consideration for future improvements.

A first and significant limitation lies in the limited empirical validation of the model, which was tested on the single use case of the Smart Water Management (SWM) project developed by Al maviva, which also served as starting point for its definition and development process. Although explicitly designed to be generalizable across different projects, sectors, and organizations, by now and in the context of this study, the model's actual application remained confined to this single implementation.

If it is true that within the same application domain the model can be easily replicated and adapted to other solutions developed by different companies, especially when similar technologies are involved, it is also true that no testing has yet been conducted beyond the original case. Indeed, all Smart Water Management solutions developed by ICT companies like Al maviva usually involve the displacement and installation of the same technological inputs and, as such, if data were available, the model could be easily used to compute indicators and effectively compare different performances. Unfortunately, due to the limited amount of quantitative information, this step has not been performed within the boundaries of the work, leaving space for future researchers to do so.

More importantly, although the model was intentionally built with the aim of being extensible across sectors, its transferability to other domains or industries, such as manufacturing, energy, mobility, or healthcare, remains unverified in practice. Without additional real-world applications, it is not possible to confirm whether the model's current structure can accommodate different technological architectures, operational configurations, or regulatory constraints. Therefore, while the model shows high theoretical potential for reuse, its generalizability and robustness under diverse conditions remain assumptions, which must be tested through further empirical application before broader conclusions can be drawn.

Second, the model in its current form is conceived as a static and linear snapshot of cause-effect relationships, without incorporating any dynamic or temporal dimensions. While this structural choice was deliberate, meant to enhance the model's readability, communicability, and ease of implementation, it inevitably oversimplifies the actual complexity of sustainability-related phenomena, which often evolve over time and are shaped by non-linear interactions. In particular, the model currently does not include feedback loops, time delays, or cyclical effects, which are commonly observed in real-world systems and whose exclusion, even if motivated by the need to make the model more accessible and immediately usable, risks ignoring important dynamics such as reinforcement mechanisms, diminishing returns, learning effects, or unintended systemic consequences. For instance, improvements in one area (e.g., infrastructure efficiency) may generate secondary benefits (e.g., reduced energy consumption or increased service continuity), which in turn further influence the initial drivers, a circular logic that is entirely absent from the model's structure.

By limiting the representation to one-directional, linear relationships, the model may therefore underestimate the cumulative or compounding effects of certain interventions, and cannot support predictive or simulation-based analyses where timing and interdependencies play a crucial role. While this purposely refined simplification does not compromise the model's usability for strategic planning or qualitative mapping, it does represent a boundary to its analytical depth, especially for organizations seeking to apply it in more advanced decision-making, systems modelling, or long-term sustainability forecasting contexts.

Additionally, the model implicitly assumes that digital technologies are effectively implemented and function as intended, without disruption or deviation from their theoretical capabilities. This includes optimistic assumptions regarding data availability and accuracy, seamless system integration, and full organizational acceptance and adoption, which all are needed to support the construction of clear and idealized causal pathways but can also mask a series of practical challenges that often emerge during real-world implementation. In practice, in fact, digital transformation processes are frequently accompanied by technical inefficiencies, operational bottlenecks, and cultural resistance within organizations, with technologies potentially underperforming due to infrastructure limitations and employees manifesting disagreement or low collaboration. By not explicitly accounting for these contingencies, the model may lead to an overestimation of the sustainability benefits of digital solutions, particularly if it is applied uncritically or used to justify investment decisions without a complementary risk or feasibility assessment. As such, while the model serves as a valuable mapping and planning tool, its application should always be accompanied by a realistic appraisal of implementation readiness, organizational context, and the maturity level of the technologies involved.

10.5. Recommendations for Future Research

Building on the contributions and limitations outlined in this study, and drawing upon the solid foundations provided by the developed ESG framework and the multilayer causal model, few yet promising directions emerge for future research. Indeed, to further consolidate their theoretical robustness, practical usability, and empirical relevance, additional investigations are recommended, especially for expanding the scope of application, testing the underlying assumptions, and addressing unresolved methodological challenges that emerged during the research process.

For instance, a first and natural direction for future research involves the empirical application of the developed ESG framework to organizations operating in different sectors and industries, of different sizes, and characterized by different regulatory constraints. Indeed, while the framework was intentionally designed to be sector-agnostic and adaptable, usable in multiple operational contexts, it has not yet been

systematically applied in real organizational settings, legitimizing doubts about its effective flexibility and validity. Applying the framework across a broader range of sectors, including not only the primarily involved food, fashion, and ICT industries but also others such as heavy metals, healthcare, financial services, or public administration, would offer the opportunity to evaluate which dimensions and KPIs are widely applicable, which require adaptation, and which may be entirely missing. This would also allow researchers to assess how well the hierarchical structure and indicator definitions align with the reporting realities and data availability of companies with different sizes, maturities, and regulatory obligations, ultimately validating the framework's robustness as a reference repository while also generating sector-specific extensions or adaptations that enhance its practical value.

Similarly to the just mentioned one, a second major recommendation concerns the broader application of the multilayer causal model, starting with additional use cases within the same application field in which it was originally developed and then extending to other sectors and industries. The first valuable step, needed to officially validate the model's usability, would be to apply it across multiple Smart Water Management (SWM) projects, possibly implemented by different companies, in different regions, or with varying technological setups. Doing so would allow researchers to verify whether the causal relationships and variable structures identified in the original case are robust and consistent across comparable initiatives, and to what extent the model can support benchmarking, impact comparison, or performance evaluation across projects of the same nature.

Once this internal consistency is confirmed, a second, complementary research direction involves applying the model to other digital solutions and sectors, such as smart manufacturing, digital agriculture, mobility, or AI-powered services. These applications would help assess how well the model's structural logic holds in entirely new contexts, and whether the categories of technologies, digital levers, and operational variables require significant reconfiguration. Ultimately, this two-phase approach, consisting in a first deep validation within the SWM domain and a subsequent extension to other fields, would allow scholars to evaluate both the model's internal coherence and its external versatility, helping to position it as a genuinely transferable methodology for assessing the sustainability impact of digital transformation.

A third direction for future research involves the quantitative validation of the causal relationships defined within the model because, although the links between variables were carefully derived from academic literature, institutional reports, and technical documentation, and are therefore conceptually well-grounded, no statistical or empirical techniques were applied to confirm their strength or reliability quantitatively. Conducting such validation would enhance the model's analytical robustness and credibility, especially in contexts where precise impact attribution is required. Methods such as regression analysis, structural equation modelling (SEM),

or Bayesian networks could be used to test the consistency and explanatory power of specific causal chains across multiple datasets or case studies. This step, although not strictly necessary for using the model in strategic or exploratory settings, would be highly beneficial for increasing confidence in its predictive capacity, and for positioning the model as a research-based, data-driven tool suitable for more advanced impact assessments. Indeed, while strictly quantitative models such as Structural Equation Modelling (SEM) were originally excluded during the construction of the causal model, due to their limited interpretability and visual complexity, they could prove extremely valuable in a validation phase, particularly for testing the consistency and reliability of the relationships embedded within the model's structure.

A further opportunity for future research lies in the digitalization of the developed tools, through the creation of an interactive platform or dashboard that integrates the ESG framework and the multilayer causal model. Indeed, while the current outputs were conceived primarily as methodological and conceptual instruments, with value majorly grounded in the academic landscape, their structured and modular design makes them suitable for translation into a digital and more practical environment. Developing a dedicated tool, such as a web-based application, an Excel-based simulator, or an interactive dashboard, could significantly improve accessibility and operational usability, especially for operators seeking to apply the model without deep methodological training. Such a tool could include features like automated KPI selection based on sector or strategic goals, dynamic visualizations of causal chains, real-time impact tracking, and benchmarking functionalities. It could also be linked to internal data systems to allow for live monitoring and feedback, thus transforming the dual frameworks into a single living decision-support system, ultimately opening the door to more agile and integrated ESG management and bridging the gap between strategic planning, data collection, and sustainability reporting.

Lastly, a more optional, but highly valuable, direction for future research involves exploring ways to simplify and optimize the visualization of the causal model by focusing only on the most relevant and impactful KPIs and merge them into a single, unified map. The strength of the model lies in fact in the possibility to simultaneously account for all possible repercussions of a project on sustainability in its broader sense, including not only intentionally reached goals but also potential and conditional consequences, indirect effects, and negative drawbacks. It is exactly this comprehensive mapping to support more informed and responsible decision-making by enabling organizations to consider the broader and often overlooked implications of their actions. However, while this level of detail is particularly valuable for companies struggling to understand the full impact of their technological strategies, it may sometimes compromise clarity and immediacy of communication, especially when the focus is on quick strategic overviews or executive-level reporting. For this reason, identifying a robust method for filtering and prioritizing KPIs based on their

actual significance, certainty, or strategic importance could greatly enhance the model's usability, allowing managers, sustainability officers, and decision-makers to temporarily narrow the focus to the most critical effects, without sacrificing the model's overall integrity. Moreover, in direct connection with the above, the potential results of quantitative validation techniques such as Structural Equation Modelling (SEM) could be leveraged to communicate the relative intensity or strength of each causal link within the visualization. Doing so would in fact not only improve analytical accuracy, but also help organizations distinguish between primary and secondary levers of change, further improving prioritization, resource allocation, and the strategic deployment of digital solutions for sustainability.

In conclusion, by concretizing these future research directions, the remarkable potential of this study can be amplified, paving the way for more rigorous and transferable approaches to integrating sustainability assessment with digital transformation, an increasingly urgent endeavour in today's rapidly evolving global context.

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