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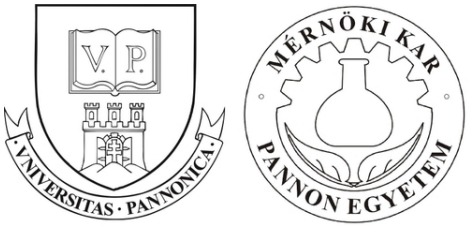
A kettős átalakulás útján: többszintű adat- és rendszer tudományi keretrendszerek a fenntartható Ipar 5.0 érdekében

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Navigating the Twin Transformation: Multi-Level Data and Systems Science Frameworks for Sustainable Industry 5.0

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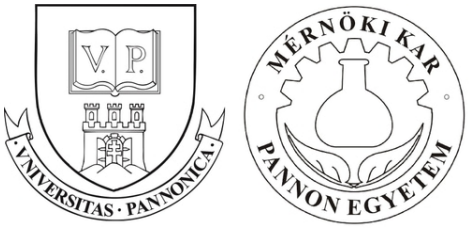
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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the

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Navigating the Twin Transformation: Multi-Level Data and Systems Science Frameworks for Sustainable Industry 5.0

The thesis was prepared for the award of a doctoral degree (PhD) within the framework of the Doctoral School of Chemical Engineering and Material Sciences at University of Pannonia

in the discipline of Bio-, environmental-, and chemical engineering sciences

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Az Európai Unio "kettős átállása" - a zöld és digitális transzformáció összekapcsolása - több szinten zajlik, ezért szintspecifikus megközelítésekre és megoldási keretrendszerekre van szükség. Ennek kapcsán a dolgozat egy többszintű eszköztárat dolgoz ki a reziliens, emberközpontú és fenntartható Ipar 4.0/5.0 átalakulások elemzésére, tervezésére, priorizálására és megvalósítására. Globális szinten egy hír- és hálózattudományi módszertant mutat be, amely a GDELT adataiból többrétegű hálók segítségével térképezi fel az SDG-k országonkénti megjelenését, a figyelem és hangulat alakulását, valamint az országok közötti kapcsolódásokat, fókuszpontokat. Regionális szinten a Triple Helixre épülő Ipar 4.0+ felkészültségi indexet javasol NUTS-2 régiókra, nyílt mutatókkal (oktatás, munkaerőpiac, innováció, befektetés, technológia), melyet PROMETHEE II/GAIA, PCA, SRD és P-SRD módszerekkel elemez, és amely összefüggést mutat a GDP-vel, innovációval és versenyképességgel. Szervezeti szinten egy minőségfunkció-kibontásra és hálózatelemzésre épülő keretrendszer kapcsolja össze a GRI témaszabványokat és SDG-célokat 18 Ipar 5.0 megoldáscsaláddal, kiegészítve az Operator 4.0 és emberközpontú menedzsment elemeivel, hogy az ESG-összhangú fejlesztés és riporting kulcsténye zői és szinergiái azonosíthatók legyenek. Végül folyamat-szinten adatvezérelt üzleti folyamatmenedzsment irányelv valósul meg egy CNC gyártósor újratervezésével, bemutatva a horizontális/vertikális integrációt és a mérhető teljesítményjavulást. A hozzájárulások együtt egy adat- és rendszer-tudományi alapú útvonalat adnak a globális helyzetképtől a regionális szakpolitikai támogatáson és szervezeti priorizáláson át a gyártósori végrehajtásig, elősegítve a zöld- és digitális átállás megvalósítását.

UNIVERSITY OF PANNONIA

Abstract

Faculty of Engineering
Department of System Engineering

Doctor of Philosophy

Navigating the Twin Transformation: Multi-Level Data and Systems Science Frameworks for Sustainable Industry 5.0

by Tímea Czvetkó

The European Union's "twin transition"—linking green and digital transformation—unfolds across multiple levels, calling for level-specific approaches and solution frameworks. In this context, the dissertation develops a multi-level toolbox for evaluating, planning, prioritizing, and implementing resilient, human-centric, and sustainable Industry 4.0/5.0 transformations. At the global level, it presents a news- and network-science methodology that, using GDELT data and multilayer networks, maps the country-level salience of the SDGs, the evolution of attention and sentiment, and cross-country linkages and focal points. At the regional level, it proposes an Industry 4.0+ readiness index for NUTS-2 regions, built on open indicators (education, labor market, innovation, investment, technology) and analyzed with PROMETHEE II/GAIA, PCA, SRD, and P-SRD methods, demonstrating associations with GDP, innovation, and competitiveness. At the organizational level, a framework grounded in quality function deployment and network analysis connects the GRI Topic Standards and SDG targets with 18 Industry 5.0 solution families, complemented by Operator 4.0 and human-centric management elements, to identify the key factors and synergies of ESG-aligned development and reporting. Finally, at the process level, a data-driven business process management guideline is realized through the redesign of a CNC production line, demonstrating horizontal/vertical integration and measurable performance improvements. Taken together, these contributions provide a data- and systems-science-based pathway from the global situational picture, through regional policy support and organizational prioritization, to shop-floor execution, thereby advancing the realization of the green and digital transition.

PANNONISCHE UNIVERSITÄT

Auszug

Fakultät für Ingenieurwissenschaften
Fachbereich für Verfahrenstechnik

Doktor der Philosophie

Lösungen für Industrie 4.0 und 5.0 mit Daten- und Systemwissenschaftstools

von Tímea Czvetkó

Die „doppelte Transformation“ der Europäischen Union – die Verknüpfung von grüner und digitaler Transformation – vollzieht sich auf mehreren Ebenen und erfordert daher ebenspezifische Ansätze und Lösungsrahmen. Vor diesem Hintergrund entwickelt die Arbeit ein mehrstufiges Instrumentarium zur Planung, Priorisierung und Umsetzung resilienter, menschenzentrierter und nachhaltiger Industrie-4.0/5.0-Transformationen. Auf globaler Ebene wird eine nachrichten- und netzwissenschaftliche Methodik vorgestellt, die auf Basis der GDELT-Daten mithilfe mehrschichtiger Netzwerke die länderspezifische Sichtbarkeit der SDGs, die Entwicklung von Aufmerksamkeit und Stimmung sowie länderübergreifende Verbindungen und Brennpunkte kartiert. Auf regionaler Ebene wird ein auf der Triple-Helix-Logik beruhender Industry-4.0+-Readiness-Index für NUTS-2 -Regionen vorgeschlagen, aufgebaut auf offenen Indikatoren (Bildung, Arbeitsmarkt, Innovation, Investitionen, Technologie). Der Index wird mit PROMETHEE II/GAIA, PCA, SRD und P-SRD analysiert und zeigt Zusammenhänge mit BIP, Innovation und Wettbewerbsfähigkeit. Auf Organisationsebene verknüpft ein auf Quality Function Deployment (QFD) und Netzwerkanalyse basierender Rahmen die GRI-Themenstandards und SDG-Ziele mit 18 Lösungsfamilien der Industrie 5.0, ergänzt um Elemente von Operator 4.0 und menschenzentriertem Management, um Schlüsselfaktoren und Synergien ESG-konformer Entwicklung und Berichterstattung zu identifizieren. Auf Prozessebene wird eine datengetriebene Leitlinie des Business-Process-Managements anhand der Neugestaltung einer CNC- Fertigungslinie realisiert und damit horizontale/vertikale Integration sowie messbare Leistungsverbesserungen demonstriert. In ihrer Gesamtheit bieten die Beiträge einen daten- und systemwissenschaftlich fundierten Pfad vom globalen Lagebild über die regionale Politikunterstützung und organisatorische Priorisierung bis zur Umsetzung auf dem Shopfloor und fördern so die praktische Realisierung der grünen und digitalen Transformation.

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Nomenclature

AI Artificial Intelligence

ANOVA Analysis of Variance

BPM Business Process Management

BPMN Business Process Model and Notation

BPR Business Process Reengineering

CAM Computer-Aided Manufacturing

CNC Computer Numerical Control

CORDIS Community Research and Development Information Service

CPS Cyber-Physical System

CRISP-DM Cross-Industry Standard Process for Data Mining

CRISP-ML(Q) Cross-Industry Standard Process for Machine Learning with Quality Assurance

DSR Design Science Research

DT Digital Twin

ERP Enterprise Resource Planning

ESG Environmental, Social and Governance

ETER European Tertiary Education Register

GAIA Geometrical Analysis for Interactive Aid

GBQ Google BigQuery

GDELT Global Database of Events, Language, and Tone

GDP Gross Domestic Product

GERD Gross Domestic Expenditure on Research and Development

GKG Global Knowledge Graph

GRI Global Reporting Initiative

GRID Global Research Identifier Database

GVA Gross Value Added

I4.0 Industry 4.0

I4.0+ Regional Industry 4.0 readiness concept/index

I5.0 Industry 5.0

ICT Information and Communication Technology

IoT Internet of Things

KPI Key Performance Indicator

MA-Graph Microsoft Academic Graph

MES Manufacturing Execution System

ML Machine Learning

NUTS Nomenclature of Territorial Units for Statistics

NUTS-2 Second level of the NUTS regional classification

OEE Overall Equipment Effectiveness

P-SRD PROMETHEE-based Sum of Ranking Differences

PCA Principal Component Analysis

PROMETHEE Preference Ranking Organization Method for Enrichment Evaluations

QFD Quality Function Deployment

R&D Research and Development

RCI Regional Competitiveness Index

RII Regional Innovation Index

RIS Regional Innovation Scoreboard

RPA Robotic Process Automation

RQ Research Question

SDG Sustainable Development Goal

SIDS Small Island Developing States

SQL Structured Query Language

SRD Sum of Ranking Differences

Triple Helix University–Industry–Government innovation model

UN United Nations

USPTO United States Patent and Trademark Office

WBG World Bank Group

Chapter 1

Introduction and motivation of the thesis

This chapter presents the research topics of the thesis, explains how Industry 4.0 and 5.0 initiatives and problems intertwine from global to local perspectives, and sets out the detailed problem formulation, research questions, required tasks, and guiding frameworks.

1.1 Introduction of the research topics

The European Union has highlighted digital transformation and sustainability as key drivers of future competitiveness, framed within the twin transition: the integration of green and digital policies [7]. In this context, Industry 4.0 (I4.0) and Industry 5.0 (I5.0) represent critical paradigms for developing resilient, human-centric, and sustainable production systems. While Industry 4.0 emphasizes cyber-physical systems, automation, and horizontal and vertical data integration, Industry 5.0 builds on this foundation to strengthen human-centricity, sustainability, and resilience in industrial ecosystems [8]. Digital transformation is an important component of an ongoing twin (green and digital) transition but to contribute to sustainable competitiveness - complex approaches and system thinking are needed in transformation processes. This means focusing on building the skills, organizational capabilities, information flows and operational models [7].

Despite the growing body of literature, there remain several challenges in operationalizing these paradigms across different levels of analysis, from global sustainability monitoring to local process optimization. The primary goal of this thesis is to develop a toolkit of models and methodologies that provide frameworks and support strategy-making for Industry 4.0 and 5.0 analysis and adoption for multilevel transformation including global, regional, organizational and process level.

Therefore, this thesis proposes a multi-scale framework for developing Industry 4.0 and 5.0 solutions, integrating systems science and data-driven approaches at the global, regional, organizational, and process levels.

At each level diverse problems and challenges are detected, which requires targeted tasks and methods. This multi-scale framework as shown in Figure 1.1, and each level is discussed more in detail in the following paragraphs. In Figure 1.1, each level is distinguished by a different color. The tools used throughout the thesis are color-coded based on the level at which they were applied. For example, network analysis was applied at both the global and organizational levels, while the organizational level additionally incorporated the quality function deployment method.

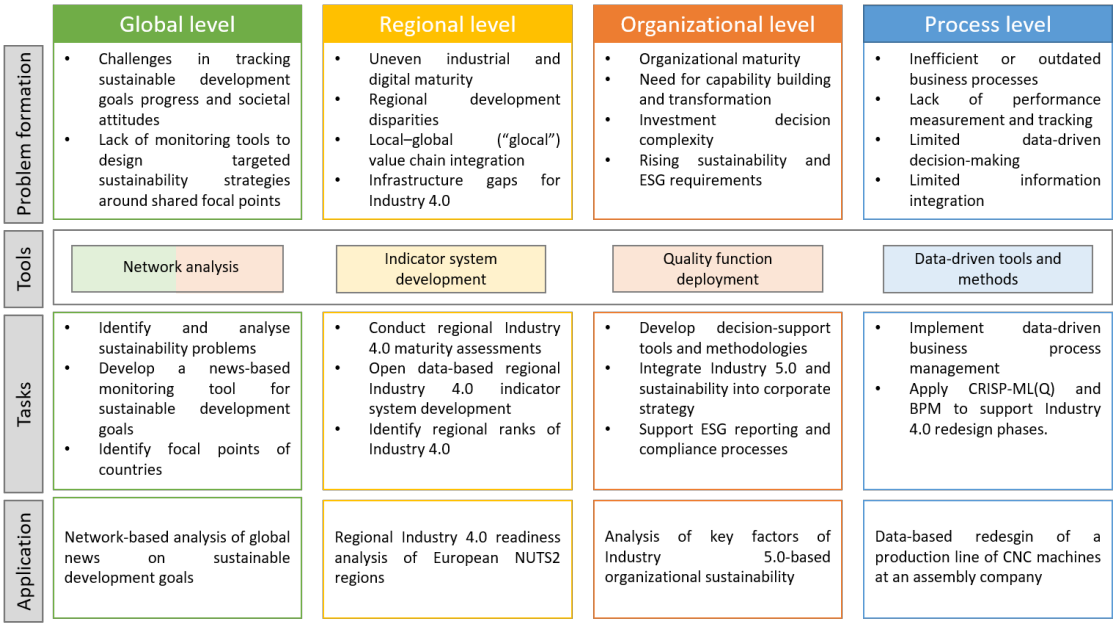


FIGURE 1.1: Schematic framework of the research topics (Source: author's own work)

Global approach

At the global level, the twin transition is framed by universal agendas such as the UN Sustainable Development Goals (SDGs) and the associated SDG Index [9] and Dashboards, which provide composite country-level assessments of sustainable development performance [10]. These global indicators are essential for benchmarking progress and identifying lagging goals and regions, but they rely mainly on official statistics that are often incomplete, updated infrequently, and unevenly available across goals and countries, particularly in the environmental domain [10]. At the same time, the emerging Industry 5.0 paradigm calls for a sustainability-driven, human-centric and resilient industrial model at the global scale, but conceptual and empirical work on how this paradigm is reflected in public discourses and problem perceptions is still at an early stage [11].

A growing body of research shows that news media and other large-scale text sources form a crucial part of global sustainability governance by shaping how societies perceive environmental and social risks, responsibility and acceptable solutions [12]. Sustainability-related media coverage exhibits strong regional differences, and no homogeneous global agenda exists even on high-profile topics such as climate change or poverty [13]. Recent studies therefore propose to complement SDG indicator systems with big-data approaches that analyse news in order to monitor SDG-related narratives and their evolution over time [14]. For example, Sufi et al. map 135,000 news articles from 100 countries to all 17 SDGs and use polarity-based sentiment profiles and principal component analysis to identify clusters of countries with similar sustainability narratives [15], while Raj et al. apply sentiment analysis, topic modelling and predictive modelling to GDELT headlines on artificial intelligence and SDG 1 (No poverty) to characterise media framings of technology-driven development [16]. These contributions illustrate the potential of large-scale news databases such as GDELT to support SDG monitoring, but they typically focus on selected thematic areas, use relatively short time windows, or analyse countries in isolation. The literature still lacks integrated, scalable monitoring tools that systematically connect individual SDGs to country-level news dynamics, capture the co-occurrence structure among goals and topics, and reveal how global sustainability attention is redistributed during crises and transitions.

In light of these gaps, Figure 1.1 highlights the need for a global news- and network-based SDG monitoring block, that can complement conventional SDG indices.

- *Relevance of the topic:* Global sustainability and Industry 5.0 debates are increasingly mediated by news and digital platforms, yet most policy dashboards ignore these attention dynamics.
- *Problem formulation:* Existing global indicators are often aggregate and incomplete, they provide limited insight into how SDGs appear jointly in public discourse, how countries are embedded in issue networks, or which topics are systematically neglected.
- *Required tasks:* Analytical tools are needed that classify large-scale news streams into SDG-related themes, construct multi-layer networks linking countries, SDGs and topics, and derive network-based indicators of sustainability attention, similarity and potential diffusion paths.

These tasks are directly addressed in this thesis. Building on the ideas summarised in Figure 1.1, Chapter 2 (Thesis I) develop a global-level monitoring framework that intertwines world news with the SDGs. News articles are mapped to SDG-related categories and represented in multilayer networks of countries and goals, and network metrics are used to detect clusters and trends in global sustainability narratives. In this way, the thesis provides a concrete methodological answer to the global-level problems outlined above and offers a complementary discursive perspective to indicator-based SDG assessments.

Regional approach

Regions have a crucial role in the twin transition as they mediate between global sustainability agendas and organization-level investment decisions, concentrating skills, infrastructures, innovation systems and governance arrangements that condition how Industry 4.0 and 5.0 technologies can be deployed. This transformation requires national and regional governmental responses and readiness for initiation, development, and sustainability [17]. Place-based innovation and smart specialisation policies explicitly recognise that digital transformation and green transition must build on regional strengths [18]. At the same time, the capacity of regional economies to generate and adopt new technologies is unevenly distributed and closely linked to labour market dynamics and socio-economic shocks [19], and local systems of industrial specialisation follow distinct transformative or obsolescence paths depending on their innovation, docking and translational capabilities [20]. While numerous Industry 4.0 readiness and maturity models have been proposed,

systematic reviews show that most of them operate at the organizational or national level, often as consultancy-type checklists, and rarely provide transparent, open data-based assessments of regional readiness [21]. This gap is particularly crucial due to regional disparities in human capital, research capacity, technological infrastructure and innovation performance strongly influence where Industry 4.0 and 5.0 solutions can realistically scale [21].

Figure 1.1 emphases a regional block that evaluates Industry 4.0 readiness at NUTS-2 level using open data and multi-criteria analysis. The main issues and methodological requirements at this level are:

- *Relevance of the topic:* Regional ecosystems determine how twin-transition investments translate into jobs, innovation and resilience, therefore policy design needs robust information on the spatial distribution of Industry 4.0 potentials.
- *Problem formulation:* Existing readiness models rarely focus on regions, often rely on proprietary data, and provide limited diagnostic insight into which specific dimensions (skills, innovation, connectivity, etc.) constrain a region's transition capacity.
- *Required tasks:* At this level, analytical frameworks must define a conceptually grounded, open-data-based indicator system for regional Industry 4.0 readiness, construct composite indexes and rankings with transparent multi-criteria methods, and relate the resulting I4.0+ profiles to broader measures of regional development and competitiveness.

In Chapter 3 (Thesis II) these tasks are discussed. A regional Industry 4.0 readiness index is developed for European NUTS-2 regions and evaluated with a rich toolkit of multivariate and multi-criteria methods (including PCA, PROMETHEE-based rankings and SRD-type robustness checks). The analysis reveals determinative factors of regional Industry 4.0 readiness and regional ranks.

Organizational approach

At the organizational level, the twin transition realized as concrete portfolios of technologies, work systems and management practices. The Industry 5.0 agenda

explicitly reframes digital transformation as a human-centric, sustainable and resilient aspiration, requiring enterprises to align investments in cyber-physical systems, AI and robotics with worker well-being, environmental performance and long-term societal value creation [8]. Concepts such as the Operator 4.0 highlight the emerging role of workers as smart, connected human-cyber-physical actors who collaborate with robots and digital systems in socially sustainable factories [22]. In parallel, corporate sustainability management has increasingly adopted the SDGs and Environmental, Social and Governance (ESG) [23] principles as strategic reference frameworks, while standards such as the Global Reporting Initiative (GRI) [24] support the measurement and disclosure of sustainability impacts. ESG is not limited to reporting: it influences governance structures, risk management, investment priorities, stakeholder relations, performance management, and operational decision-making. However, neither high-level sustainability frameworks nor reporting standards alone provide a design logic for selecting and combining Industry 4.0/5.0 solutions that address specific sustainability requirements. Recent work argues that Industry 5.0 should be understood as a strategic framework that integrates sustainability management with digital transformation and risk management, yet concrete methods that link SDG- or ESG-based requirements to families of Industry 5.0 solutions are still scarce [25]. Quality Function Deployment (QFD) and its environmental and green extensions [26] have long been used to translate stakeholder requirements into technical characteristics, and have been adapted to identify organizational sustainability factors [27] and to improve sustainability characteristics [28]. However systematically mapping sustainability goals to Industry 5.0 solutions and operator-centric work design remains underexplored.

Accordingly, Figure 1.1 introduces an organizational block in which SDG- and GRI-based sustainability requirements are connected to families of Industry 5.0 solutions through a structured mapping.

- *Relevance of the topic:* Organizations must decide which digital and cyber-physical solutions to prioritise in order to improve both sustainability performance and human-centric work, while also complying with ESG and reporting expectations.

- *Problem formulation:* There is a fragmentation between ESG-oriented sustainability strategy and governance, sustainability measurement and reporting through standards such as GRI, technology roadmapping, and human-centric work design. Managers often lack tools that translate strategic ESG objectives and reporting requirements into concrete Industry 5.0 development portfolios and operational interventions.
- *Required tasks:* Organizational level methods should systematically translate SDG and GRI topics into structured sustainability requirements, link these requirements to Industry 5.0 solutions using QFD-type matrices, and analyse the resulting bipartite network to identify key leverage points and synergies.

Therefore, Chapter 4 (Thesis III) provides a response to these needs by proposing an Industry 5.0-oriented QFD framework in which SDG- and GRI-based sustainability requirements are mapped onto a taxonomy of Industry 5.0 solutions and operator roles. The resulting matrix is analysed as a network to identify central solutions and clusters of tightly linked requirements, thus operationalising the organizational block of Figure 1.1 and providing concrete guidance for technology selection and prioritisation in human-centric, sustainable organizations.

Process approach

The impact of the twin transition is ultimately realized at the process level, where products are manufactured, services are delivered and resources are consumed.

In this thesis, the term process level is used primarily in the sense of intra-organizational operational processes, that is, the design, execution, monitoring and improvement of workflows within a focal production system. Although process phenomena may extend beyond firm boundaries in supply chains and service networks, such inter-organizational process structures are considered here only as an important contextual extension and not as the primary empirical focus.

Business Process Management (BPM) provides a well-established discipline for modelling, analysing, redesigning and monitoring organizational processes, and has become a central pillar of digital transformation [29]. The rise of Industry 4.0 and 5.0 and the availability of rich event data have given rise to process mining and data-driven BPM, which e.g. use event logs to discover, analyse and enhance processes, as well as utilizing advanced technologies and large language models, which are increasingly applied in manufacturing and logistics [30]. At the same

time, machine-learning process models such as CRISP-ML(Q) emphasise the need to integrate quality-assured analytics into the full lifecycle from business understanding to deployment and monitoring [31].

Despite these advances, both the BPM and Industry 4.0 literatures highlight unresolved challenges, which are "rooted in the inadequacy of traditional BPM approaches to adapt to the dynamic and knowledge-intensive nature of contemporary organizational environments. The challenges and constraints facing BPM are multifaceted, spanning across organizational, human and cultural, information technology and knowledge management dimensions" [32]. Frameworks often address either process modelling and redesign or analytics and machine learning, but do not fully integrate BPM life-cycle phases with data-science life cycles in a way that supports continuous, data-driven process evolution [33]. Furthermore, there is still limited guidance on how to concretely embed Industry 4.0 technologies such as IoT, digital twins and advanced analytics into existing process architectures, particularly in small and medium-sized manufacturing enterprises [30]. Existing methodologies rarely connect process-level improvements explicitly back to higher-level Industry 5.0 objectives such as human-centric work systems and sustainability performance.

Figure 1.1 indicates a process-level block focused on data-driven BPM for Industry 4.0 and 5.0.

- *Relevance of the topic:* Process-level analysis determines efficiency, flexibility, resource use, and working conditions. It is where regional readiness and organizational strategies must be translated into operational routines.
- *Problem formulation:* Organizations face methodological fragmentation, and BPM tools, Industry 4.0 technologies and ML life-cycle models are often applied in isolation, which hinders systematic, quality-assured exploitation of process data for improvement.
- *Required tasks:* There is a need for integrated guidelines that position data-driven analysis and CRISP-ML(Q) within the BPM life cycle, specify how Industry 4.0/5.0 technologies (e.g. sensors, CNC data, digital twins) can be used to support process discovery, diagnosis and redesign, and are validated through real industrial case studies.

Therefore, Chapter 5 (Thesis IV) address these requirements. The thesis proposes a guideline that intertwines the BPM life cycle with CRISP-ML(Q) and applies it to the redesign of a CNC production line. Event data and contextual information are used to discover and improve process variants, define key performance indicators and evaluate alternative redesign scenarios.

Intertwining of the research levels

The Industry 4.0 and 5.0 transition is a multi-scale phenomenon, which results in a systems and data-focused, complex, multi-objective thinking and strategy making across our way of managing processes, deciding on organizational strategies, regional investments or the global assessment of public perception on the transformation and the focus points.

In this thesis, the abovementioned four levels are assessed: global, regional, organizational and process level, where each level represents a research topic. In Table 1.1 the intertwining of each topic is introduced.

TABLE 1.1: Intertwining of global-regional-organizational-process levels in sustainability-oriented Industry 4.0 and 5.0. Cells below the diagonal represent the bottom-up perspective, while cells above the diagonal represent the top-down perspective. (Source: author's own work)

Bottom-up \ Top-down	**Global**	**Regional**	**Organizational**	**Process**
Global	Global studies track how sustainability and Industry 4.0/5.0 narratives evolve, anchoring comparable benchmarks, targets, and shared vocabularies across countries.	International policies, standards, and media focus point shape NUTS2 funding priorities, program design, and adoption incentives for I4.0/I5.0 and including e.g. new skill developments.	Global frameworks (SDGs, ESG) and investor expectations translate into firm-level commitments, reporting duties, and technology roadmaps.	High-level norms cascade into operational requirements (energy intensity, safety, traceability, etc.) that must be encoded in day-to-day workflows.
Regional	Standout regional programs, data, and shocks feed back into the worldwide narrative, shifting agendas, taxonomies, and best-practice examples.	Comparing regional readiness identifies patterns and gaps (investments, technology, higher education, innovation, labor market) that inform smarter place-based strategies.	Regional readiness (investments, technology, higher education, innovation, labor market) enables firms to adopt and sustain I4.0/I5.0 capabilities.	Local infrastructure and incentives (data-driven tools, training, etc.) ease factory-floor digitalization and data access that modernize processes.
Organizational	Corporate strategies, disclosures, and coalitions amplify or challenge global narratives, shaping norms, standards, and capital flows.	Leading firms catalyze regional ecosystems via supply chains, demonstration effects, and talent demand that lift the maturity baseline.	Organizations design an Industry 5.0-aligned sustainability strategy and institutionalize it through ESG/GRI reporting practices, so planning, execution, and disclosure reinforce each other in continuous improvement.	Strategy becomes executable through data-driven BPM, embedding real-time KPIs and controls into everyday work.
Process	Aggregated operational evidence on efficiency, safety, and emissions informs global targets, best practices, and market expectations.	Proven process innovations diffuse through supplier networks and training systems, upgrading regional productivity and sustainability.	KPI signals and process insights support management, reallocating resources and refining I5.0 enablers.	Continuous data-driven improvement cycles refine workflows and automation logic, lifting conformance, quality, and resource efficiency over time.

Table 1.1 summarizes how the twin transition unfolds across four analytical scales (global, regional, organizational, and process) and how each level both shapes and is shaped by the others. Cells below the diagonal the bottom-up, while cells above the diagonal represents the top-down perspectives. Top-down influences include global narratives, standards, and investor expectations cascading into regional funding priorities, firm-level roadmaps, and operational requirements (e.g., energy intensity, safety, and traceability). Bottom-up dynamics show how operational KPIs and process innovations accumulate into organizational learning, diffuse through regional ecosystems, and ultimately inform global benchmarks and best practices.

Together, the cells illustrate a dense web of policy, capability, and data flows: regional readiness conditions firm adoption,

while organizational strategies are shaped not only by regional development trajectories but also by national and sector-specific policy frameworks, since sustainability integration and disclosure priorities vary across industries [34].

These strategies are institutionalized through ESG-oriented governance, risk-management, investment, and performance-management practices, while GRI and other reporting standards support the measurement and disclosure of related impacts. Their operational implementation is supported through data-driven BPM, which connects strategic objectives with process models, data flows, KPIs, and continuous feedback loops. The matrix thereby motivates the multi-scale framework of the thesis for Industry 4.0 and 5.0 by making explicit the bidirectional linkages required for human-centric, resilient, and sustainability-oriented transformation.

However, it should be emphasized that the four analytical levels of the thesis do not represent a closed or exhaustive hierarchy of all relevant governance and implementation scales. In particular, the national level and sector-specific policy frameworks play an important mediating role between global agendas, regional capabilities, organizational strategies and process-level execution. These dimensions are therefore treated in this thesis as cross-cutting contextual layers rather than as separate analytical levels. Future extensions of the framework could explicitly incorporate national and sectoral dynamics.

The direct research questions and proposed frameworks are introduced in Section 1.2.

1.2 Research questions and proposed frameworks

This section formulates the research questions associated with each analytical level and introduces the corresponding preliminary thesis statements, proposed frameworks, and methodological approaches. The preliminary thesis statements provide an explicit overview of the expected scientific contributions of the research, while the research questions specify the analytical problems addressed by the individual studies. The detailed methodological development, empirical substantiation, and discussion of the results are presented in Chapters 2-5, whereas the final, evidence-based thesis statements are consolidated in Section 6.2.

Thesis I. - Global level identification and analysis of sustainability-related issues through news network analysis

Conventional SDG monitoring provides limited insight into the media visibility, tone, and relational structure of sustainability issues across countries. Therefore, this thesis develops a news- and multilayer-network-based framework that connects GDELT content with SDG-related taxonomies to support the comparative analysis of country profiles, thematic focal points, and co-occurrence patterns.

RQ I.I *What terms directly related to sustainable development goals can be identified in the taxonomic system of news?*

Establishing an SDG-aligned vocabulary enables consistent mapping of news to sustainability themes, improving comparability and coverage assessment across sources and time.

RQ I.II *What is the tone of the news regarding each of the sustainability issues?*

Analyzing the tone of sustainability issues supports the detection public perceptions.

RQ I.III *What are the differences between countries in terms of SDG news? How similar are the focal points?*

Cross-country divergence in focus areas reveals priority shifts, which can inform strategic planning.

RQ I.IV *Which countries cooperate in terms of various sustainability issues?*

Identifying countries co-occurence in sustainability news can support the analysis of objective interlinkages.

Proposed framework and method:

At the global level, the framework operationalizes systematic news analytics as a macro-level tool for monitoring how attention concentrates on sustainability themes, what the public tone is, and how countries interlink around SDGs. Using the GDELT database, the approach constructs a labeled multilayer network that maps country profiles across the 17 SDGs, enabling cross-country comparison of attention, sentiment, and co-occurrence structures. Beyond measurement, the global layer supports the identification of emerging issues and cooperation patterns, positioning news analytics as a bridge from public discourse to policy-relevant insight.

Thesis I. is formulated and discussed in details in Chapter 2.

Thesis II. - Regional level Industry 4.0 readiness measurement

Existing Industry 4.0 readiness models primarily focus on organizations or countries and provide limited support for transparent regional comparison. Therefore, this thesis develops an open-data-based Industry 4.0+ readiness framework for NUTS-2 regions that integrates five regional development dimensions and combines multicriteria and multivariate methods for ranking regions and identifying influential readiness factors.

RQ II.I *What are the key dimensions and open data indicators of measuring regional Industry 4.0 readiness?*

Measuring regional preparedness through open-data indicators can support transparent and reproducible benchmarking across NUTS2 regions, enable timely progress monitoring, and provide an evidence base for targeting policies.

RQ II.II *What are the most determinative factors of regional Industry 4.0 readiness?*

The identification of driving factors can support strategy and policy making by revealing the highest-leverage intervention points, guiding capacity-building and investment priorities, and informing scenario design and sensitivity analysis.

RQ II.III *What is the regional Industry 4.0 rank?*

The objective measure of identifying regional rank can support comparative evaluation.

RQ II.IV *How Industry 4.0 readiness index correlate with economic, innovation and competitiveness indexes?*

The correlation analysis can support validation and relevance checks, and help anticipate spillover effects of Industry 4.0 investments on regional competitiveness.

Proposed framework and method:

At the regional level, the thesis introduces an Industry 4.0+ (I4.0+) readiness index for NUTS-2 regions built from open indicators spanning education, labor market, innovation, investment, and technology. A composite indicator is made from the gathered set of 101 indicators.The index couples complementary multicriteria and exploratory techniques: PROMETHEE

II/GAIA for preference-based ranking and visualization, PCA for variance structure and biplot interpretation, SRD for indicator diagnosticity versus a gold standard, and P-SRD to evaluate inter-criteria similarities by applying SRD to the PROMETHEE input matrix. External validity checks include correlations with GDP, the Regional Innovation Index (RII), and the Regional Competitiveness Index (RCI), supporting relevance and robustness.

Thesis II. is formulated and discussed in details in Chapter 3.

Thesis III. - Organizational level Industry 5.0 sustainability development

Sustainability standards define high-level organizational expectations but provide limited guidance on how these requirements can be translated into concrete Industry 5.0 development priorities. Therefore, this thesis develops a QFD- and network-analysis-based decision-support framework that connects SDG targets and GRI Topic Standards with Industry 5.0 solution families and reveals their direct, indirect, and community-level relationships.

RQ III.I *How organizations can prioritize Industry 5.0-related organizational developments?*

Clear prioritization translates scarce resources into the highest sustainability and productivity gains, avoids technology-push dead ends, and enables defendable investment roadmaps and KPI targets.

RQ III.II *What is the connection between SDGs, sustainability requirements and Industry 5.0 solutions?*

Mapping requirements to concrete I5.0 solutions ensures that initiatives are purpose-driven (not tool-driven), aligns projects with stakeholder expectations and disclosures, and creates traceability from objectives to technology choices.

RQ III.III *What is the indirect interconnection between SDGs, GRI and Industry 5.0 development and what communities do they form?*

Revealing indirect links and community structures uncovers not only potential conflicts but also synergistic, co-developable solution bundles whose impacts reinforce each other and can be managed jointly.

Proposed framework and method:

At the organizational level, the thesis develops a Quality Function Deployment (QFD)–grounded framework that connects SDG targets, GRI Topic Standards, and Industry 5.0 solution families (augmented with Operator 4.0 and human-centric management), thereby aligning strategic sustainability requirements with implementable technological pathways.To address complexity and reveal structure, the QFD mapping is also cast as bipartite (and tripartite) networks, enabling structural analysis of direct and indirect relationships across the SDG–GRI–I5.0. This representation supports community detection (Louvain) to uncover synergistic clusters—where organizational reporting and technological developments reinforce each other—and

to flag potential gaps. The combined QFD and network view provides an auditable trail from disclosure expectations to project portfolios while preserving expert tailoring for firm-specific strategy.

Thesis III. is formulated and discussed in details in Chapter 4.

Thesis IV. - Process level Industry 4.0 and 5.0 development

Industry 4.0 technologies and data-science methods are often applied separately from the Business Process Management lifecycle, limiting their systematic use in continuous process development. Therefore, this thesis develops an integrated data-driven BPM framework that connects Industry 4.0 tools and CRISP-ML(Q) activities with process discovery, analysis, redesign, implementation, and monitoring.

RQ IV.I *How the business process management cycle can be improved by Industry 4.0 tools and methods?*

Industry 4.0 capabilities, tools and methods enable real-time visibility and human-centric assistance within business process management cycle, reducing variability and accelerating continuous improvement.

RQ IV.II *How standard process models of data mining and machine learning can be integrated into business process management?*

Integrating CRISP-ML(Q) into the BPM life cycle ensures governed, reproducible ML across every phase, linking problem framing to deployment and monitoring, so data-driven models can reliably improve process KPIs through explicit quality gates and continuous feedback loops.

Proposed framework and method:

At the process level, the work specifies a data-driven Business Process Management (BPM) and integrated with digital technologies across the BPM life cycle. The development cycle proceeds from digital maturity assessment and threat/opportunity analysis to a to-be agenda, prioritization, an I4.0 roadmap, and implementation/monitoring, thereby operationalizing continuous improvement. The framework embeds CRISP-ML(Q) within BPM phases to ensure governed, reproducible analytics from problem framing to deployment and monitoring, so that models reliably improve process KPIs via explicit quality gates and feedback loops.

Thesis IV. is formulated and discussed in details in Chapter 5.

Chapter 2

Global sustainability assessment through network and news analysis

The concepts of Industry 4.0 and 5.0 not only rely on internal operational data, but also on external socio-technical, socio-regulatory context. Sustainability is one of the key pillars of Industry 5.0, leading research to investigate sustainability problems in more depth. Identifying and analyzing sustainability problems requires targeted analytical tools due the issues deeply interlinked nature and evolve across scales. News analytics provides a tool for global sustainability analysis by quantifying public and policy attention to sustainability themes and sustainable development goals (SDG) across countries. Therefore, this chapter positions systematic news analytics as a macro-level tool that reveals where attention concentrates, what is the public opinion, and how countries interlinked regarding sustainability issues.

2.1 Introduction

News plays a significant role in conveying objectives and major focus areas of both governmental as well as public interests. Furthermore, news can be considered to be creative source of information [35]. The level of public awareness and prioritisation regarding sustainability issues can be determined across countries and regions [13]. The analysis of news can define areas that gain attention, moreover, governmental strategies and action plans to be identified as sustainable development and

environment-related news coverage depend mostly on political institutions and experts as sources of news [36]. News analysis can also play an active role in terms of defining the status of the road map for localizing the SDGs. Generic patterns in sustainability-related media agendas can contribute to support addressing challenges [13]. The localization of the SDGs is critical as local spaces are key factors of the successful implementation and preservation of the goals [37].

A comprehensive overview of articles concerning sustainable development goals by the different approaches of media analysis is detailed in our related publication "The intertwining of world news with Sustainable Development Goals: An effective monitoring tool" [1]. 113 articles are classified according to their relevance with regard to describing the 17 SDGs. The overview of articles revealed a gap in terms of defining SDG areas through news and media appearance and highlighted that there is a need for a systematic tool for country-specific and thematically targeted news-based monitoring of sustainable development.

In this research, the GDELT database [38] is used to explore news about sustainable development goals as well as measure trends and similarities between countries around the world. The proposed methodology can be used to determine which sustainability issues are becoming more critical in a given country or region, or what trends can be observed in the field of sustainability communication.

In connection to world news, the following analytical questions can be formulated:

- What terms directly related to sustainable development goals can be identified in the taxonomic system of news?
- What is the tone of the news regarding each of the sustainability issues?
- What are the differences between countries in terms of SDG news? How similar are the focal points?
- Which countries cooperate in terms of various sustainability issues?

To answer these questions a labelled multilayer network is created to identify the profiles of nations/regions based on the news categorized according to the 17 sustainable development goals and the related targets and indicators.

The novelty of the research is hidden in the broadened exploration of news that overcomes boundaries - it links the multi-level analysis of SDGs with evidence-based events, governmental strategies as well as public interests. The news centred

approach can model interconnections between nations regarding sustainable development actions and strategies as well as supports decision-making mechanisms. Furthermore it is possible to measure public awareness, which is closely related to social acceptance and support for the national sustainable development strategies. The appearance of the sustainable development goals in the news has not been directly measurable previously. The main advantage of the developed tool is that the analysis of the occurrence of goals in the published news can be performed in an automated way for any time period.

Therefore, the contribution and the structure of the chapter are as follows:

- In Section 2.2 the method of news-based analysis of sustanability development goals is detailed.
- In Section 2.3 the sdg-related news analysis is carried out and discussed.

2.2 Method of news-based analysis of sustainable development goals

In this section, the methodological steps are discussed from data acquisition and categorization up until the formation of multi-layered networks. The proposed methodological workflow is suitable to build multi-layered networks to reveal the focal points between news and specific contents and taxonomies. The key assumption is that connecting topic-specific news and their spatial connection can reveal the sensitivity of country to a given topic as well as detect interconnections between keywords. Regarding the analysis sustainable development goals the spatial coverage is considered at the country level, while the temporal horizon is considered in the year of 2019. This chapter presents the connection between the specific content of sustainable development goals and the taxonomy of the World Bank as well as the segments of the My World 2015 survey, followed by a presentation of the development of analytical Structured Query Language (SQL) queries. The reader is then guided through the description of the network formulation from the extracted information to determine the news and SDG.

The workflow of sustainable development goals-related acquisition of news gained from The GDELT Project is The steps of the analysis are summarized in Figure 5.4.

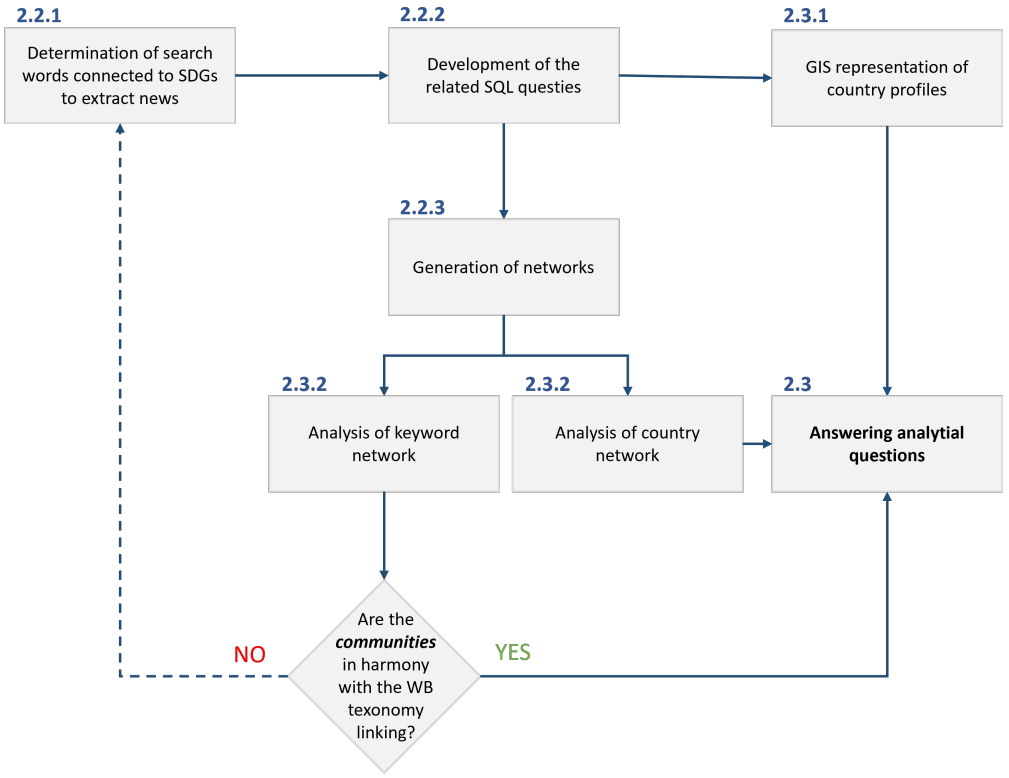


FIGURE 2.1: The proposed workflow of the news-based analysis of sustainability issues and the corresponding subsections (Source: Ref. [1])

World news on sustainable development goals is a good illustration of the mentality of countries' concerning the 2030 Agenda. The published news stories are labelled along with the ontologies in the GDELT Project, which allows for their thematic analysis if the ontologies related to the given issue are selected, in our case, the SDGs based on the taxonomy of the World Bank. The taxonomy of the World Bank has been reviewed and the categories related to SDGs selected.

The data were extracted from the GDELT's Global Knowledge Graph (GKG). GDELT has already been used to estimate the future level of violence in Afghanistan [39], explore disasters and their determinants [40], determine the risk of upcoming social unrest events and predict indicators related to the instabilities of country [41] or to analyze peace and conflict data [42].

Two methods were used for the extraction, namely the "standard" way, which involves Google Big-Query engine, and a self-developed Python-based engine. For short queries, and validation, Big-Query was used, for more analytical and long time frame analysis, the offline Python-based engine was used.

The results of the queries can also be analyzed using Geographic Information System (GIS) techniques, thus revealing how the countries are sensitive to SDG issues and how much news is reported about SDGs. Multidimensional networks comprised of queries aim to shed light on the relationships between countries and topics. The ontological assignments with regard to the SDGs can be checked based on the identified keyword communities, however, it is important to emphasize that due to the interconnectedness of SDGs the validation requires expert knowledge.

2.2.1 SDG-aligned keyword selection for news extraction

WBG Topical Taxonomy refers to the World Bank Group's topical knowledge domains and areas of expertise, whilst the segments determined by the My World 2015 survey contributed to the formation of Agenda 2030. These data was used as a basis to approximate these categories within the 17 goals - involved targets and its indicators.

The selection from topics with regard to WBG Topical Taxonomy and association with the development goals happened through expert sampling. These associated search words are discussed in Ref [1] in Appendix Table A.1.

The segments of the My World 2015 survey are the following: A good education, Better healthcare, Better job opportunities, An honest and responsive government, Affordable and nutritious food, Protection against crime and violence, Access to clean water and sanitation, Support for people who can't work, Better transport and roads, Equality between men and women, Reliable energy at home, Political freedoms, Freedom from discrimination and persecution, Protecting forests, rivers and oceans, Phone and internet access, and Action taken on climate change.

The formulation of sustainable development goals is concise and ambitious, therefore, the World Bank categories are preferably linked on the basis of the keywords in the more detailed description of the indicators. For example, the following keywords can be extracted from the indicators of SDG 15: 'ecosystem', 'forest', 'land', 'protected', 'biodiversity', 'red list', 'mountain', 'wildlife' and 'species'. Links are based on expert knowledge, however, the methodology allows them to be validated.

For SDG 13, "Take urgent action to combat climate change and its impacts", 5 targets and 7 indicators were declared. To measure this goal, the number of countries with disaster risk reduction strategies, number of affected persons by disaster, mobilized financial support and other policy strategic measures are used. Table 2.1 shows that topics were selected that are very closely related to the concept of SDG 13 and its indicators. The following keywords extracted from the SDG 13 targets and indicators that linked with the World Bank categories: 'disaster', 'natural disaster', 'policies, strategies and planning', 'education', 'climate change mitigation and adaptation', 'impact reduction', 'early warning'. The experience of studies discussing the interconnectedness of SDGs was taken into consideration in the application of the search words [43] [44]. One of the main advantages of the proposed methodological development is that it can be applied flexibly in any subject area, such as the representation of the circular economy or industry 4.0 topics in world news. In the table, the column WB_SHORT refers to the ontology number of the World Bank, that empowers the traceability, the column WB_NAME describes the description connected to WB_SHORT.

Table 2.1: Search words applied to proximate SDG 13: Climate action and SDG based on the World Bank Group Topical Taxonomy (Source: Ref. [1])

SDG 13: Climate action			
My World 2015			
UNGP_CLIMATE_CHANGE_ACTION (Action taken on climate change)			
WB_SHORT	**WB_NAME**	**WB_SHORT**	**WB_NAME**
WB_587_	Poverty and Climate Change	WB_1844_	Market-Based Climate Change Mitigation
WB_821_	Disaster Risk Reduction	WB_1787_	Natural Habitats
WB_823_	Post Disaster Recovery and Reconstruction	WB_3138_	Natural Disaster
WB_3358_	Man-Made Disasters	WB_1705_	Disaster Preparedness
WB_1770_	Climate Change and Vulnerable Groups	WB_580_	Low Carbon Development
WB_142_	Energy and Water	WB_705_	Economic Shocks and Climate Change
WB_156_	Groundwater Management	WB_1838_	Climate Risk Screening
WB_1798_	Water Pollution	WB_1750_	Climate Change Adaptation Impacts
WB_1998_	Water Economics	WB_1752_	Climate Change Adaptation in Coastal and Marine Areas
WB_1831_	Environmental Crime and Law Enforcement	WB_1753_	Gas-to-Power
WB_849_	Environmental Laws and Regulations	WB_1758_	Transport and Climate Change
WB_158_	Water Resources and Climate Adaptation	WB_1772_	Private Sector and Climate Change
WB_140_	Agricultural Water Management	WB_1773_	Climate Change Impacts
WB_537_	Urban Energy Efficiency	WB_1774_	Climate Forecasting
WB_538_	Energy Efficiency in Industry	WB_1777_	Forests
WB_1756_	Energy and Climate Change	WB_1791_	Air Pollution
WB_520_	PPP in Energy and Power	WB_1795_	Ozone Depleting Substances (ODS)
WB_2673_	Jobs and Climate Change	WB_1837_	Climate Change and Disaster Risk
WB_1075_	Industry Policy	WB_1839_	Ozone Layer Depletion and Climate Change
WB_1979_	Natural Resource Management	WB_1849_	Public Climate Finance
WB_963_	Natural Resources Law	WB_1850_	Private Climate Finance
WB_2639_	Climate Efficient Industries	WB_1878_	Carbon Capture and Storage
WB_582_	Greenhouse Gas Accounting	WB_570_	Early Warning Systems
WB_810_	Climate Change Adaptation in Urban Areas	WB_573_	Climate Risk Management
WB_1841_	Short-lived Climate Pollutants (SLCPs)		

Sustainable development goals are not evenly covered by indicators, and in the case of indicators, there is a significant lack of data, which makes it challenging to monitor their fulfilment. This is especially true of SDG 13, where hardly any measurable indicators are present. This is why it is essential to find additional

data sources for which one of the promising tools is the news analysis presented in this research. It is generally true that the SDG indicators do not characterize the awareness and participation of the society, however, the proposed methodological development allows these factors to be taken into account.

2.2.2 News extraction from GDELT Database

GDELT uses some of the world's most sophisticated natural-language and data-mining algorithms, including the world's most powerful deep-learning algorithms, to extract and monitor world news. GDELT consists of the Event Database, which captures worldwide activities (events), as well as the Global Knowledge Graph (GKG), which records and entwines people, organizations, locations, themes, taxonomies, sources, tone and events of news into a network. The important attributes of GKG can be seen in Table 2.2.

GKG enables the co-occurrence of people, locations or organizations that empower analysis concerning the relationships between parties to be determined.

Table 2.2: Important attributes of an article for the network creation (Source: Ref. [1])

Name	**Notation**	**Description**	**GDELT attribute**
Id	id	Identifies an article. This is a unique attribute of all articles	GKGRECORDID
Date	t_i	Identifies the publication date of the article	V2.1DATE
Location	L_i	List identifying the locations mentioned by the article	V1LOCATIONS
Themes	D_i	List identifying the topics	V2ENHANCEDTHEMES
Sentiment	s_i	Shows the average tone of the article. This ranges between -100 (extremely negative) and +100 (extremely positive)	V1.5TONE

GDELT Global Knowledge Graph, which offers scalable, cost-effective, cloud-based opportunities to analyse huge amounts of data, is available as a queryable dataset in the Google BigQuery (GBQ).

GBQ is comprised of a Structured Query Language (SQL)-like syntax, with lots of additional data processing tools, e.g. unnesting (separating columns into multiple rows) and regular expression capturing. This domain-specific language is often used in programming and data management. The queries are based on a schematic SELECT query, which captures the main details of the GKG database, namely location, date, topics and tone.

Although GDELT provides a large-scale and globally consistent dataset, its use can introduce limitations. Redundant news items, geolocation inaccuracies, and automated topic classification errors may introduce noise into the analysis, while uneven media coverage across countries can create structural bias. In addition, the database does not capture audience reach, and the tone indicator is a simplified proxy of sentiment.

Therefore, the results should be interpreted as patterns of media visibility and thematic co-occurrence rather than as direct measures of real-world importance or societal impact.

2.2.3 Network-based representation of sustainability news

Network analysis provides a graphical representation of complex patterns of relationships between variables [45]. Therefore, beyond the relationships of countries with regards to sustainability news, the relationships between countries and topics can be described. Furthermore, this method can serve as validation of the selection and categorization of keywords which occurred as a result of expert sampling, as if the keywords are clustering significantly (creating a community), a strong interrelationship can be observed between them and the classification can be confirmed as suitable.

Network analysis carries great potential to:

- explore and visualize relationships.
- identify central nodes - countries/keywords - by defining the number of connections (degrees) to the node or analysing the frequency pathway between other nodes (betweenness).
- detect clustering nodes (communities), e.g. countries systematically involved in a certain topic.

GDELT Global Knowledge Graph allows the co-occurrence exploration of locations (e.g. countries), people as well as themes that appear in news, which can serve as a basis for the network formation.

The analysis is based on the multidimensional network representation of the avaliable information. A multidimensional network can be defined as, nodes (V), edges (E) and dimensions (D):

$$\begin{aligned} G &= (V, E, D) \\ E &= \{(u, v, d), u, v \in V, d \in D\} \end{aligned} \tag{2.1}$$

An edge is expressed as a connection between two nodes u and v, in a dimension d. In our case, the nodes are countries and the dimensions are sustainable goals as well as their subcategories. The network is generated using the GDELT geolocation, topic recognition and sentiment analysis. The sentiment analysis part will be discussed later, for now, the creation of the simplest network will be concentrated on. GDELT geolocates each article to countries and cities according to the locations mentioned in the article. If an article contains or mentions, two different countries, this is an edge in the network between the two countries. Upon the identification of an edge, the dimension must be accounted for. The network will be multidimensional, therefore, the categories of the article will define which layer the previously mentioned edge appears in.

An article is regarded as a quadruplet of the article's id (i), its publication date (t_i), the identified set of locations mentioned within it (L_i), the dimensions and tags of the article (D_i) and its sentiment (s_i). Table 2.2 summarizes the connections between the GDELT database and our notations.

$$a_i =< i, t_i, L_i, D_i, s_i > \tag{2.2}$$

Based on GDELT, two types of network building are followed. One approach is when the nodes of the network are the topics (integrated SDGs), where the edges are the news, the dimension of the edges is the countries or groups of countries, while the weight of the edges is the number of pieces and/or tone.

The other option is when the nodes of the network are countries and edges are the news of a particular topic, where the weight of the edges can be determined from the number of articles. Networks can be generated directly with developed SQL queries, but can also be generated based on the downloaded database.

The presented tool analyzes the occurrence of sustainable development goals in the news and characterizes the emphasis of the goals based on the assigned World Bank Group Topical Taxonomy categories. A limiting factor of the approach is that the very general categories that are related to a lot of news can mislead the analyst, so it is not enough to interpret aggregated results at the SDG level, but also to control them at the taxonomy level. The tool can be further developed if different taxonomies are not given equal importance to the goals, but the labels that best describe the goals are represented with higher weights.

2.3 Results and discussion

The results section shows how world news are related to sustainable development goals. This is the only piece of research that uses a broad-spectrum, systematic, multilingual monitoring tool to describe the sustainability information flow objectively. This methodological development allows to be continuously monitored throughout the world through online queries, thus measuring the social acceptance of SDGs and encouraging participation in terms of their implementation, as well as helping countries around the world to share experiences concerning their problems and successes, which is essential for the implementation of the Agenda. Based on the news, the significance and tone of SDGs in different countries can be modelled on its own. Based on the network analysis, the joint occurrences of the topics can be explored from which the presented approach can be validated. In the news, the spatial allocation of sustainability issues can be measured based on common countries, and countries with similar problems or achievements can be grouped. The analysis can be performed both holistically and in a goal-oriented fashion.

The analysis presented for 2019 can be carried out for any time period. The developed tools and the extracted data are publicly available on the authors' website: abonyilab.com.

In the following, the representation of the proposed method is described through the global overview of the Sustainable Development Goals, after which climate change goal (SDG13) is presented in detail and finally, the SDG interlinkages are illuminated by the interpretation of the generated networks.

2.3.1 Geographic representation of the sustainable development goals in the world news

Based on the proposed method it can be determined, that how often the SDGs occur in the news in different countries worldwide. The percentages of world SDG news are summarized in Figure 2.2. Cold colors represent lower percentages, while warm colors represent higher percentages. Map cutouts were selected based on the Global Burden of Disease Study [46]. For the quantization of the data equal-frequency binning has been applied, in which we divided the dataset into bins that all have an equal number of frequencies. It should be noted that the frequency of news within a given topic must be interpreted with caution, as the analysis captures occurrence rather than underlying causes. Consequently, observed patterns may be influenced by external factors such as political campaigns, major events, or crises.

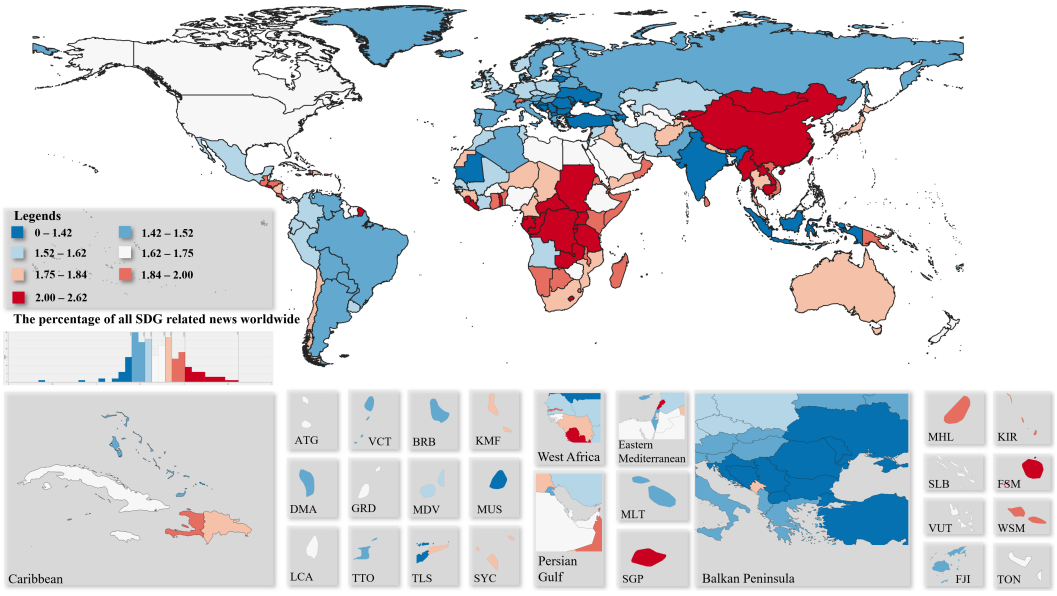


FIGURE 2.2: Percentage of SDG-related world's news. (Source: Ref. [1])

Figure 2.2 shows that the share of sustainability news, even in the most sensitive countries, is only around 2.6%. Sierra Leone leads the flow of information on SDG news with 2.62%, followed by Rwanda with 2.47% and Liberia with 2.44%. There are only 2 countries where the share of SDG-related news is less than 1%, Saint Pierre and Miquelon and Bouvet Island. The distribution shown in Figure 2.2 shows that Africa as well as East and Southeast Asia are the general hot spots of SDG news.

In Eastern Europe, the appearance of SDGs in the news lags slightly behind that in Western countries. Considering that the maximum value is around 2.6%, it follows that the scale moves in a relatively narrow range. In Europe, sustainability related news is most common in Switzerland, at 1.94%. For Small Island Developing States (SIDS), the relative frequency varies. There are countries where more SDGs news appear, such as Singapore (2.04 %) and Federated States of Micronesia (2.29 %) and some where less than Mauritius (1.4 %) or Dominica (1.52 %).

The tone of the SDG-related news is illustrated in Figure 2.3. For the quantization of the data equal-frequency binning has been applied, in which we divided the dataset into bins that all have an equal number of frequencies. Due to the relatively high number of topic areas, no particular extremes can be observed in Figure 2.3. Even the unweighted average tone is represented the aggregate indicator is suitable for presenting the general opinion of the countries concerning the SDGs.

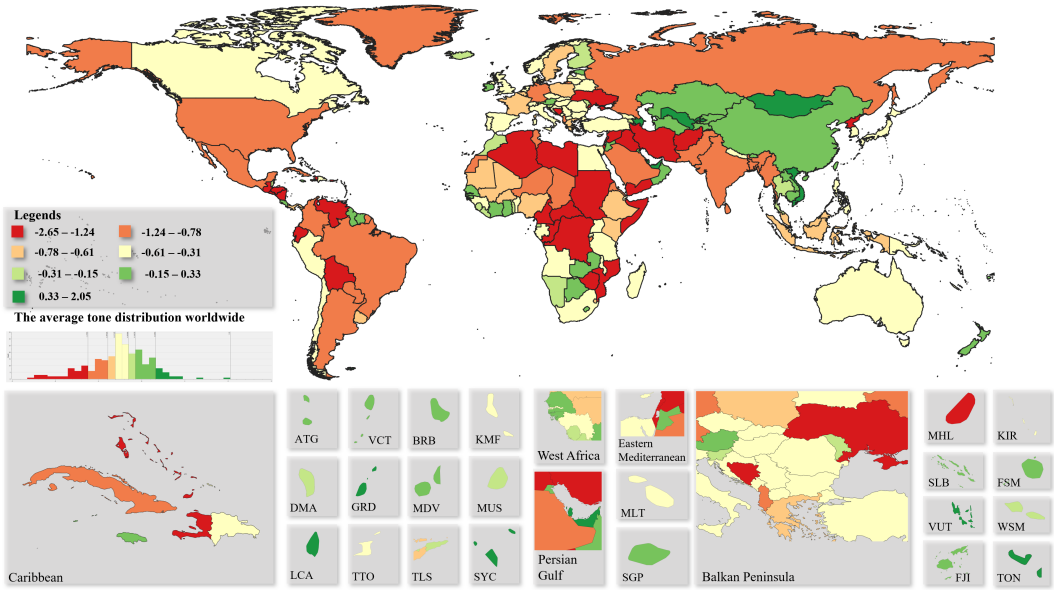


FIGURE 2.3: Average tone of SDG related world's news. (Source: Ref. [1])

Based on Figure 2.3, the most positive (+2.05) is found in Saint Kitts and Nevis, followed by Macau with 1.42. All other positive tones are below +1.00. Other positive countries are Saint Lucia scoring 0.92, Seychelles with 0.82, and then the United Arab Emirates with 0.73. The most pessimistic country is Christmas Island with a tone of -2.65, followed by Libya with -2.44 and Iran with -2.43. A very interesting correlation is observed between Figures 2.2 and 2.3. The most SDG-related news sees the light of day in Africa, but the news is also the most negative here, therefore, a joint analysis of quantity and tone is recommended.

For Small Island Developing States, perceptions of SDG are generally positive (except in Marshall Islands, where -1.25), but overall, the news are more negative in the world as a global picture. One reason for this may be that awareness raising works more effectively if the emphasis is on the negative consequences. In any case, the regional patterns are well understood in the average tone of the news, however, they may be of further interest for analysis of tones at the different SDGs, which is beyond the scope of the present research. Nevertheless, the proposed tool we have developed is directly suitable for conducting such researches. In this case, the average tones can also be interpreted on a wider scale.

The impact of climate change is perhaps the most obvious in the world's news, so the application of the methodology to address this issue will be described separately.

Figure 2.4 shows the percentage of world news related to action against climate change in 2019. In the figure, red colors indicate higher frequencies, while colder blue colors indicate lower frequencies. Map cutouts were selected based on the Global Burden of Disease Study [46]. For the quantization of the data equal-frequency binning has been applied, in which we divided the dataset into bins that all have an equal number of frequencies.

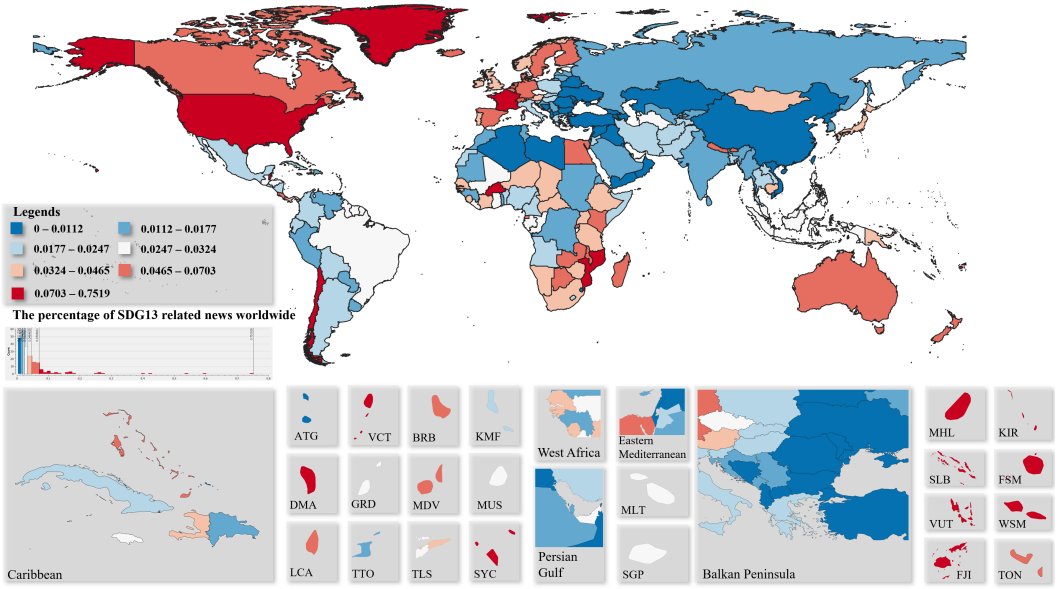


FIGURE 2.4: Percentage of climate change action related to world news. (Source: Ref. [1])

As a proportion of all the news in the countries of the world, Tuvalu publishes the most news related to climate change, 0.75% to be exact. The second most

common is the U.S., where 0.6% of the news is about climate change. The third place is located in the Arctic Ocean, namely the Svalbard archipelago, with 0.54%. The least amount of news concerning climate change appears in Anguilla, 0.003%. In general, the analysis shows that news about climate change is more relevant in small island states. Climate induced risks for small islands includes sea level rise, tropical and extratopical cyclones, changes in rainfall patters and the increase of air and sea surface temperatures [47]. This fact has so far not been sufficiently taken into account with regard to the implementation of the 2030 Agenda, as the indicators set for the Climate Action (SDG 13) goal in themselves fail to take into account such groupings of countries.

In general, climate change is more prominent in countries that, due to their geographical location, have a more significant relationship with the seas or oceans. In Europe, France has the most news on climate action, with 0.12%, an order of magnitude higher than the European average.

News media play a significant role in informing and engaging citizens in sustainability issues [48], therefore, the tone of news indicates their general opinion. The average tone of the countries can be seen in Figure 2.5. Pessimistic countries are denoted in red, while those with a positive attitude are labelled in green and nations that are neutral in yellow. For the quantization of the data equal-frequency binning has been applied, in which we divided the dataset into bins that all have an equal number of frequencies.

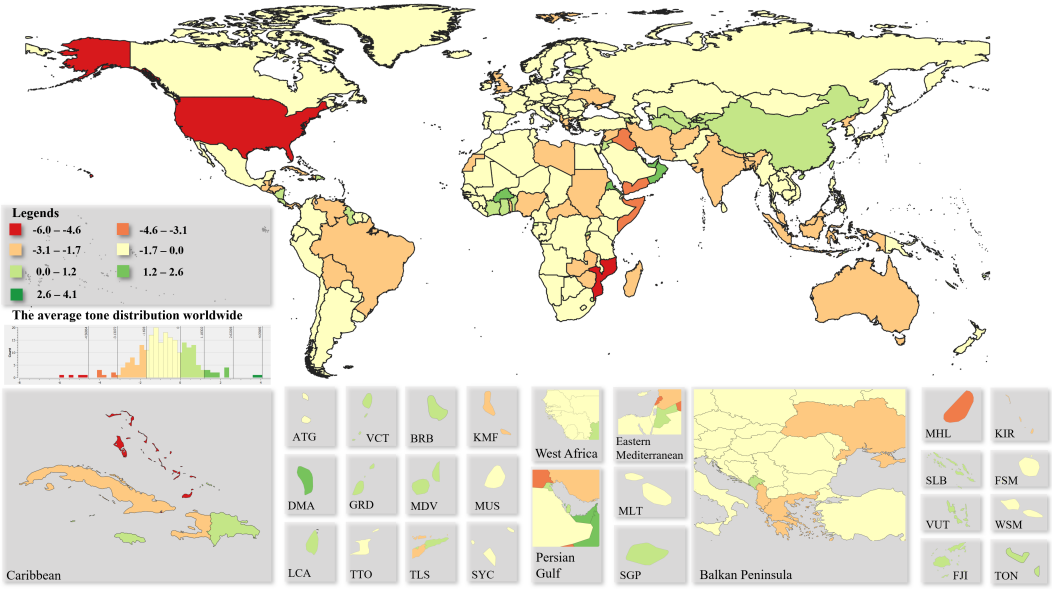


FIGURE 2.5: Average tone of climate change action related to world news. (Source: Ref. [1])

According to the news, Cape Verde is the most negative country with regard to climate change, where the average tone is -6. In second place is the United States with a value of -5.5 and in third is The Bahamas with -4.9. The most optimistic country is Aruba, with an average tone of 4.1, followed by Monaco with a value of 3.7 and then Macau with a score of 2.4. It can be seen that the average tone is usually neutral in the world. Further interesting research could be a separate analysis of very negative and very positive news, which can be done directly with the methodology developed in the present research.

2.3.2 Network analysis of the intertwinning of sustainable development goals and world news

Sustainable development goals are closely interlinked, a fact that is also true for news categories and the typical published news profiles of the countries around the world. In the following, networks are used to illustrate the complex interrelationships of the intertwining of SDGs and news. The network of ontologies characterizing sustainable development goals is illustrated in Figure 2.6. In the network, the size of the title of the topics is proportional to its degree of centrality, while the thickness of the links between the issues is proportional to the number of news and the colour shows the average tone.

As is shown in Figure 2.6, the identified modules in the network are related to the same topics, which are highlighted by the colours of the nodes, therefore, the connections between the ontologies of the World Bank and the sustainable development goals considered can be validated. The highest degrees of centrality with regard to the nodes in the network are the 'human resources for public sector', 'pharmaceuticals', 'metal ore mining', 'education skills development and labor market' and 'health promotion and disease prevention'. The edges of the network are predominantly red, which means that sustainability news tends to be negative. If the developed queries are used, the development of the network of topic areas over time, the interest in sustainable development, the flow of information, and the speed of responding to environmental problems can all be measured. This research aims to present query-based monitoring as a new option in the field of sustainability assessment. Analyzing changes in the news over time is a promising future research direction.

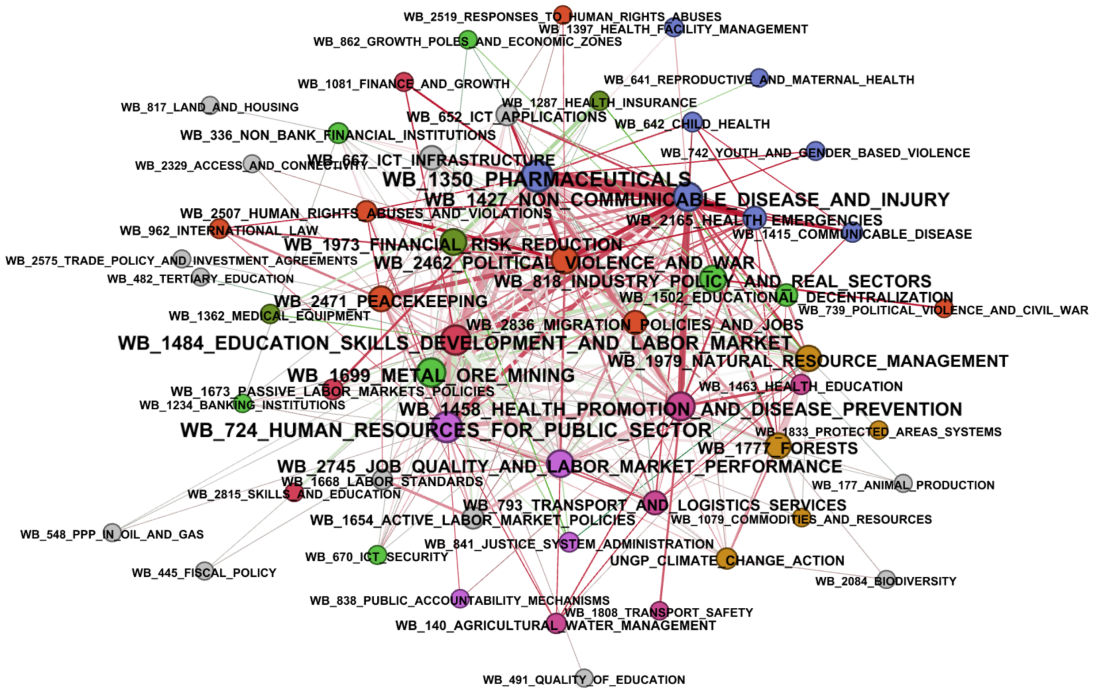


FIGURE 2.6: The intertwining of world news and SDGs (Source: Ref. [1])

This research has presented a methodological development based on the combination of news with SDGs that can contribute to the effective delivery of the 2030 Agenda. There are differences between countries around the world in both the proportion and tone of SDG-related news. The proposed methodology is also suitable for holistic and goal-oriented analyses, which were presented across all objectives and on the example of SDG 13. The overall hot spots of sustainability news are mainly in Africa as well as East and Southeast Asia, moreover the most negative tone recorded in Africa. In contrast, in the case of climate change, the United States and small island states are more in focus. These facts outline the foundations for exploring future focal points of SDG 10: Reduced inequalities, nevertheless, they can also help fill in information gaps to identify potential areas for collaboration (SDG 17). Tracking news can also help to better understand the state of technical goals worldwide, such as SDG 6 "Clean water and sanitation," where SDG indicators focus mainly on infrastructure, while social aspects are highly underrepresented. Analyzing the news provides support for strategists in precisely this objectively difficult area to also measure modern wastewater treatment processes such as heat recovery, enzymatic wastewater treatment or membrane technology which can be measured mainly through news, across the SDG indicators it is not possible.

In Figure 2.7 the occurrences of countries in the climate action-related (SDG 13) news is represented in a network. The network identifies the intertwining of countries based on countries mentioned together in news with regard to the 13th goal.

The sizes of the nodes are proportional to their occurrence, and the edges represent those mentioned to be in collaboration, where the weight is the number of the news. The colors of the nodes were chosen according to the classes of modularity detected.

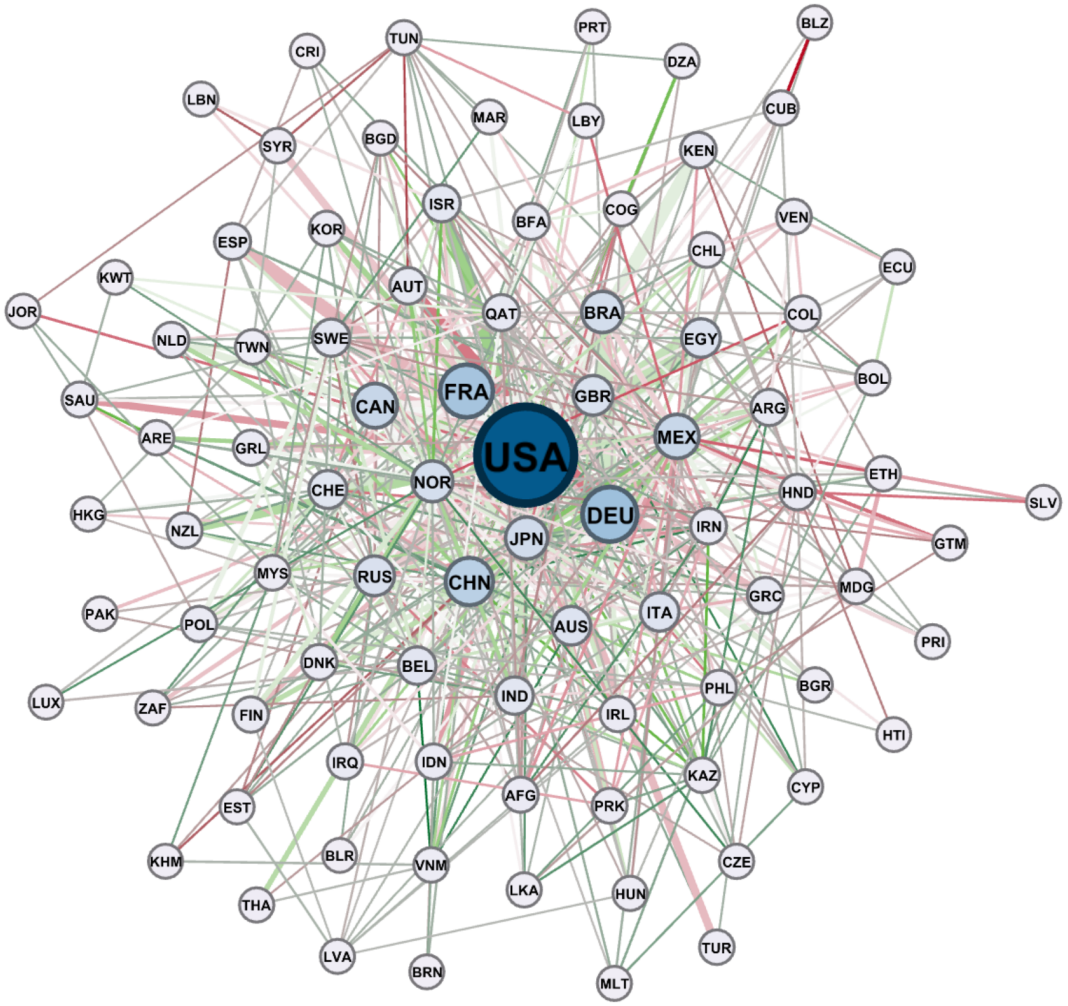


FIGURE 2.7: The intertwining of countries worldwide with regard to climate change (SDG 13) (Source: Ref. [1])

Figure 2.7 shows that the United States is most often mentioned in the world news about climate change. The U.S. can be grouped with 132 other countries, has a betweenness centrality of 0.525 and is by far the most significant hub in the network. The most weighted edges in the network are France-USA with 3343 news,

France-Germany with 3243 news, Canada-USA 3209, UK-US 2368, Russia-USA 2091, Egypt-USA 2052 and China-USA 2015. In terms of nodes, the second most central hub is France, the third is Germany, the fourth is Mexico and the fifth is India.

The provision of information encourages people to participate in environmental protection and, by involving people, makes it possible to maintain the continuity and implementation of sustainability policy in the most cost-effective way. [49]

Analyses showed that there was very little difference in the level of environmental quality concerns between developed and developing countries [49].

If the environmental preferences of agents are sensitive to environmental pollution and human capital, the economy is able to follow a balanced growth trajectory, with damped oscillations that can be addressed by environmental policy [50].

The fact that countries play a largely neutral role in the climate change news network is a good indication that we need to make serious efforts to achieve the objectives of the SDGs and the Paris Climate Agreement.

In summary, sustainable development goals can be monitored through news appearing determined by carefully selected keywords. The network of ontologies characterizing sustainable development goals determines their centrality, links and tone. The distribution of the percentage of sustainability news reveals that general hot spots are located in Africa as well as East and Southeast Asia. The average tone of the SDG-related news presenting the general opinion of countries in regard with the issues, for example, considering the average of SDG news, the most positive country is Saint Kitts and Nevis (+2.5), while the most pessimistic is Christmas Island (-2.65). Furthermore, the cooperation of countries in regard with sustainability issues can be determined by the thoughtful analysis of countries co-occurrence in the selected news.

2.4 Conclusion

The major objective of this chapter was to determine country profiles as well as interconnections according to the presence of sustainability - assessed through a news-centred network analysis. This method enables the stages of implementation

to be determined and serves as a supportive decision-making tool to contribute towards the conscious formation of a sustainable socio-economic ecosystem.

Based on the developed methodology, any SDG can be analyzed in the world news. A comprehensive analysis of 2019 shows that world news are not significantly focus on SDGs, as with all related topics accounting for only roughly 2.5% of the news are covered by SDG-related topics, even in the most sensitive countries. Sustainability news is most prevalent in Africa as well as East and Southeast Asia, with the former having the most negative tone in the region. The proposed methodology will provide essential information for future strategic planning with regard to several goals, in particular in the area of SDG 10, where addressing inequalities is a key challenge.

Through the news, not only holistic but also goal-oriented analyses can be performed. It can be seen that the role of the United States is prominent in SDG 13 and that greater emphasis should be placed on small island states in the future, because the news about climate change is mostly negative in these countries. The analysis shows that more emphasis should be placed in all countries on the appearance of SDGs in the news. Since countries are also grouped together in terms of different SDG-related ontologies, the relationship between countries can also be analyzed. It has been shown that the United States is one of the most important hubs in the network. The results will contribute to an objective SDG-based analysis of the news, thus helping to track implementation of the 2030 Agenda. The average tone of SDGs is negative, especially for African countries, while Small Island Developing States have a positive viewpoint on the 2030 Agenda. The most positive countries are Saint Kitts and Nevis +2.05, followed by Macau with 1.42. The most neative news are occured in Christmas Island with a tone of -2.65, followed by Libya with -2.44 and Iran with -2.43.

In addition to the interpretation of extreme country-level values, the results also point to broader regional patterns that deserve attention. For example, the map of climate-change-related news suggests differences between Western and Eastern Europe, while uneven patterns are also visible within Africa. These differences may reflect not only physical exposure to climate change, but also policy priorities, media structures, public awareness, economic profiles and the political salience of environmental issues. Therefore, the country-level rankings should be interpreted together with intra-continental comparisons and, where relevant, comparisons among larger-population countries.

We recommend that countries exposed to climate change (especially the SIDS) work together, while tackling the negative appearance of the United States in the news about climate change is an urgent task. The negative perception of African countries about SDGs shows that countries around the world need to put more emphasis on Reduced Inequalities within and among countries (SDG10) goal.

Social acceptance is a key element in the strategic planning of the implementation of 2030 Agenda, so we recommend that national governments inform the public about the tasks, achievements and challenges related to SDGs. A more frequent appearance in the news can be one of the positive drivers for a better understanding of sustainability issues and solutions. The presented monitoring tool can provide useful feedback to decision makers about the awareness of residents and help them learn about their attitudes.

From an Industry 5.0 perspective, the findings of this chapter suggest that the human-centric, sustainable and resilient transformation of industry is embedded in a global discursive environment, where media narratives both reflect and contribute to shaping societal expectations, perceived risks, and the legitimacy of policy and technological choices. This relationship should be understood as bidirectional, as media coverage is also influenced by existing policy priorities, political agendas, and major external events. By translating world news into SDG-related indicators and country profiles, the methodology developed here offers a macro-level monitoring framework that complements traditional statistical indicators and supports Industry 5.0 strategies aiming at sustainability and social well-being.

As a follow-up contribution to this work, an automatically and daily updated interactive analysis platform has been created. This platform enables users to explore climate change-related world news through world graphs that measure country co-occurrence in climate news, examine the geographic distribution of climate-related topics and tones, use interactive pivot tables and filters, and export climate news data. The Climate Action Macroscope is available at: `http://climatemacroscope.uni-pannon.hu/`

In this sense, the chapter directly underpins Thesis I: it develops and validates a scalable, news- and network-based monitoring tool that intertwines world news with the SDGs, identifies country clusters and key hubs, and reveals gaps and biases in sustainability attention.

From a cross-level perspective, the findings of this chapter also reveal several gaps and implications that require consideration at the regional, organizational, and process levels. The global news- and network-based analysis identifies differences in the visibility, tone, and co-occurrence structure of sustainability issues, but it does not determine whether the countries and territories concerned possess the capabilities required to respond to these issues through industrial transformation. Media attention may reveal emerging priorities, neglected topics, and potential international linkages, but it cannot directly measure the availability of skilled labour, innovation capacity, investment resources, technological infrastructure, or institutional support.

This creates a gap between the identification of global sustainability-related attention patterns and the assessment of implementation readiness. To translate global signals into actionable development pathways, the analysis must therefore be complemented by a territorially disaggregated assessment of the structural conditions that enable Industry 4.0 and 5.0 adoption. This gap motivates the regional-level analysis in Chapter 3, where open indicators are used to evaluate the readiness of NUTS-2 regions in terms of education, labour market, innovation, investment, and technology.

A further gap remains between global sustainability narratives and organizational decision-making. News-based country profiles do not specify which sustainability requirements should be prioritized by individual organizations or which Industry 5.0 solutions can address them. These questions are addressed at the organizational level in Chapter 4. Similarly, the global analysis does not provide operational guidance on how high-level sustainability priorities can be embedded in production processes, data architectures, and performance indicators; this implementation gap is addressed by the process-level framework presented in Chapter 5.

Chapter 3

Regional Industry 4.0 readiness model development

For sustainable economic development, it is crucial that Industry 4.0 and 5.0 solutions are interpreted not only in terms of technological maturity levels, but also on the basis of region-specific influencing and measurable factors. Therefore, in this chapter a regional Industry 4.0 readiness model is built on the Triple Helix (industry–university–government) framework and benchmarked at the NUTS2 level. The model integrates five core dimensions: investment, innovation, higher education and lifelong learning, labor market, and technology. Choosing NUTS2 regions ensures international comparability while aligning directly with policy design and funding allocation.

3.1 Introduction

In the rapidly changing environment, regions and cities are forced to develop their strengths to improve their overall competitiveness [51]. The challenge of today is to seize the opportunities hidden in digital transformation [52]."Digital globalization is inducing deep and productive transformations, making industrial policy necessary in order to reorientate development towards inclusive and more sustainable growth" [53]. A major development potential of a region is managing information and knowledge flows between organizations [54]. Therefore, collaborative territorial governance has to take a step forward to help small and medium-sized companies apply Industry 4.0 and simultaneously develop the region itself [55].

Knowledge flow and innovation stimulates digital transformation by inter-regional cooperation projects while focusing on the green economy and smart cities concepts. This approach can result in the long-term sustainability of economic growth, reducing environmental risks and ecological degradation as well as improving human welfare and social equity [56]. "To support policymaking processes, it is necessary to develop analytical tools exploring the determinants of the Industry 4.0 development" [57].

This regional perspective and the concept of regional Industry 4.0 (referred to as Industry 4.0+) should gain more attention in the future as it opens up opportunities for regional developments that should be managed based on public and collective strategies. A decision support tool needs to be developed for I4.0+ projects to evaluate regional I4.0 performance. Recent studies have proven the potential of defining and measuring regional development status through indicator system assessment [57], [58]. Therefore, this research aims to explore this potential and create a suitable tool to measure the I4.0 readiness of regions. A region-focused and I4.0-specific indicator system is built to provide a quantitative and comprehensively applicable concept.The developed indicator system is based on the Triple Helix model of innovation which refers that the synergies of governmental, academic, and business sectors amplify regional development [59]. The cross-collaboration of the Triple Helix actors enables a suitable and stable base for I4.0 implementation to be created and preserved. Appendix S1 underlines the importance of the Triple Helix concept by providing an overview of region-specific indicator systems utilizing the triple helix model.

In the following sections, the Industry 4.0+ (region-specific) concept and its major driving forces of development are discussed and analyzed:

- In Section 3.2 the five major dimensions of the I4.0+ readiness concept is defined and the related open data indicators are introduced.
- The method of developing and analyzing this regional readiness index is discussed in Section 3.3.
- In Section 3.4 a comprehensive analysis of the study applied to European NUTS 2 regions is carried out to measure their regional I4.0 readiness. The I4.0+ index was validated by correlation analysis using economic, innovation and competitiveness indexes, and potential application areas are identified.

Also, the possible application areas of the proposed I4.0+ index are determined.

This section reveals the necessity of measuring I4.0 readiness from a regional perspective. The core dimensions of the I4.0+ concept are determined and open data sources assigned to measure the I4.0 readiness of regions.

3.2 Dimensions of regional Industry 4.0 (I4.0+) readiness

The examination of the I4.0-related readiness models indicates a strong degree of organizational and national orientation. Appendix S2 provides an overview of the I4.0 readiness models describing the level of measurement and the areas of evaluation. Seven I4.0 readiness models are compared with regard to their scope and defined dimensions. According to the findings, five out of the seven studies defined readiness models for companies (mainly SMEs) ([60], [61], [62], [63], [64]), while one each is designed for the national [65] and city levels [66].However, recent studies have tended to pay increasing attention to the perspective of regional development in the case of I4.0. Ref. [58] developed a Regional Industry Index (RII) based on ten open data indicators applied for Bulgarian NUTS 3 regions. The study highlighted the role of the labour market, investments, enterprises, R&D and information society. Ref. [57] seeks to explore the determinants of I4.0 development using extended indicator-based SWOT analysis applied to a Polish region (Podlaskie Voivodeship). Furthermore, Ref. [67] defines the correlation between Industry 4.0 and R&D projects in relation to stages of the macroeconomic cycle. However, it can stil be claimed that the regional assessment of I4.0 readiness has not been studied extensively. Furthermore, regional readiness significantly determines the development status of both organizations and nations. Regions should sufficiently combine regional resources with new industries and technologies to avoid the efficiency trap in terms of technological innovation while focusing on industrial transformation and creating industrial opportunities [68].

Even though the analysis of Refs. [58] and [57] determines the regional development potential in a well structured way, the NUTS 2-classified and multi-source data analyses are still missing. Therefore, we see the potential in developing a

solely open data indicator-based I4.0+ index to measure the NUTS 2 regional readiness for I4.0 implementation and, as a result support decision-making processes. The developed I4.0+ indicator system is divided into five major dimensions representing regional economic growth: higher education and lifelong learning, technology, innovation, investment and the labour market. The dimensions mentioned in Figure 3.1 are strongly related to each other and aim to foster regional development and competitiveness and, therefore, improve the quality of life.



FIGURE 3.1: I4.0-related dimensions of regional development (Source: Ref. [2])

These dimensions are interrelated to the Triple Helix actors, academia (universities and research institutions), industry (organizations and the labour market) and the government. Higher education is like a driving force of knowledge creation, providing a well-educated workforce for the labour market. Moreover, this sector also supports innovative actors, such as research institutions. The innovative capability of a region can redound to the ability to apply modern-day technological developments. On the other hand, investment is essential to promote knowledge transfer. However, projects may not be implemented by enterprises or institutions without financial support. The willingness to continually learn policies can be the basis for successful scientific and technological activities [69]. The socio-technical environment integrates and shapes the governance of innovations and transformation processes [70]. All these dimensions aim to enhance the competitiveness and

development of a region. In the following, these dimensions are analyzed more in-depth, and the indicators associated with them proposed.

1. **Higher education and lifelong learning:**

   Due to constant digital transformation and innovation, the demand for an immensely skilled workforce with new skill sets is increasing [71]. Regarding the expansion of technology-based knowledge and the advent of the global economy, education is directly responsible for the evolution of industrial structures [72]. Therefore, the importance of on-demand educational training and lifelong learning activities is beyond doubt as the reskilling of the workforce facilitates the ability of people to cope with future job creation. As members of the academic sector, universities are said to be one of the drivers of regional economic development and competitiveness. They play a significant role in rebounding socio-economic advancement through studies, education, innovation and infrastructure development [73].

   Regarding the dimension of regional higher education and lifelong learning, the following indicators are considered:

   - Educational attainment level (25-64) (EDU1-4) determines the percentage of the population aged 25-64 that falls into different levels of educational attainment. Three levels of educational attainment are considered, namely 1) upper secondary as well as post-secondary non-tertiary and tertiary education, 2) upper secondary as well as post-secondary non-tertiary education, and 3) tertiary education. Therefore, by measuring the percentage of 25-64 aged population attainment in terms of higher education, this indicator can be considered as a proxy for identify the intensity of lifelong learning within regions or more specifically a proxy for the general human capital base and educational structure of the working-age population. A higher share of tertiary-educated adults indicates that a region has a broader knowledge base and a potentially more adaptable workforce, which is relevant for Industry 4.0 readiness.
   - The educational attainment level (30-34) (EDU5-7) offers a narrower perspective of the aforementioned indicator as the age group is only between 30 and 34 years old. It captures the educational profile of younger cohorts entering or recently entering the labour market. Thus,

the 25–64 indicator reflects the accumulated stock of regional human capital, while the 30–34 indicator provides information on the recent output of the education system and the future supply of highly educated labour relevant to Industry 4.0 readiness.

- The indicator of the employment rate of young people not in education and training (aged 15-34) (EDU8-35) reflects the extent to which young people who are no longer participating in education or training are integrated into employment, in some cases also considering the time elapsed since completing their highest level of education. Therefore, the indicator does not directly measure the time gap between leaving education and entering work, but rather the labour-market absorption of young people after education.
- Graduates (BSc, MSc, PhD) in Engineering, the Natural Sciences and Statistics (GRA1); IT and Information and Communications Technology (GRA2); as well as Engineering, Manufacturing and Construction (GRA3) can be some of the significant forces with regard to the I4.0-related pillar of higher education. This indicator determines the regional preparedness of providing labour to the market that is specifically skilled in I4.0. Furthermore, this output indicator can be considered from the perspective of the demand for skilled labour of regions with regard to I4.0.
- The number of students participating in study mobility programmes (ERA1-2) indicates the additional number of students leaving and arriving in a region to study in the fields of Science, Mathematics and Computing, as well as Engineering, Manufacturing and Construction.

2. **Labour market:**

Opportunities as a result of Industry 4.0 made developing businesses conscious as continuous innovation is no longer an option for success but necessary to remain competitive in the market. Careful and conscious business innovation has become a priority, which has changed the perception of job content. As a result of digitalization and robotization, there is a growing need for high technology and knowledge-intensive services. According to a report from the World Economic Forum (WEF), 23 to 37 % of companies are planning to invest in robotization between 2018 and 2022. This transformation brings about 133 million new jobs and help to balance out almost 75

million jobs displacements [74]. Governments and institutions face the pressing issue of identifying skill development models to ensure job opportunities for the working age population [75].

Three indicators are considered to identify the readiness of regions with regard to the I4.0-related labour market, namely:

- Employment in the technology and knowledge-intensive sectors (HTE1-8) reflects the percentage of employment in the chosen economic activities related to I4.0.
- The number and tone of I4.0-related media appearances (GDC, GDT) within regions is a creative way of measuring how many regions deal with the issues and/or results of the relevant field (innovation, automation, research and development as well as SMEs).
- The number of institutions (GRC) within a region indicates the available employment opportunities as well as the possibility for open innovation and collaboration with external parties. Within this indicator, we consider research-related organisations registered in the Global Research Identifier Database [76], namely educational institutions, companies, healthcare institutions, governmental institutions and nonprofit organization.

3. **Innovation:**

The innovation capability of a region is a critical factor in terms of I4.0 readiness, as it empowers a company or region to be competitive [71]. Innovation can occur through the utilization of technological developments as well as idea and knowledge creation [77], in which the Triple Helix actors play a significant role [78]. Their collaboration increases the efficiency of finding solutions to innovation and sustainability-related challenges [79].

The following indicators are taken into account with regard to the I4.0-related innovative actions of regions, namely:

- The indicator of Human Resources in Science and Technology (HRS1-10) reflects the regional intensity of employment in science and technology. It determines which regions are advanced and which need to improve.

- Patent applications in I4.0-related field (PAT) indicates the innovation capability according to the ability and willingness of a region to adopt new ideas and technological developments.
  These I4.0-specific areas are the following: Additive manufacturing technology, Nanotechnology, Machines or engines in general; Engine plants in general; Steam engines, Controlling; Regulating, Computing; Calculating, Counting, Signaling, Information and Communication Technology (ICT) especially adapted to specific fields of application.
- Publications by category (PAP) aims to measure the number of publications per region over a given periof of time. This indicator reflects the intensity of research and development actions in the academic sector.
  These categories are the following: Industrial engineering, Operations management, Process engineering, Transport engineering, Operations research, Simulation, Knowledge management, Control theory, Telecommunications, Mechanical engineering, Computer engineering, Software engineering, Manufacturing engineering, Machine learning, Data mining, Mathematical optimization, Control engineering, Regional science, Embedded systems, Artificial intelligence, Process management, Reliability engineering, Systems engineering, Management science, Data science.
  A strong correlation can be observed between productivity indicators with regard to the number of publications and university-industry co-authored publications that exist [80].
- Employment in the technology and knowledge-intensive sectors (HTE1-8) is a driver of innovative progression as employees in these sectors are the "initiator" of knowledge transfer and development.

The dimension of innovation interweaves all sectors that are considered drivers of regional I4.0 development, namely higher education and lifelong learning, the labour market and technology, as well as investment.

4. **Investment:**

   Financial initiatives play a significant role in terms of skill evolution, innovation and job creation through policy-making. The industry has been a target of investments as it is expected to be a driver of competitiveness, innovation, jobs and wealth [81]. The responsibility of the budget allocation for R&D must be divided among the Triple Helix actors [78]. Furthermore,

I4.0-focused regional development can only be maintained with collaboration between the actors (academia - key of knowledge, industry - production key, government - key of stable interaction).

Both R&D personnel and R&D expenditures considered to be elements of innovation with regard to the regional innovation system [82], therefore, the dimension of I4.0-related investment studies the following two indicators:

- Total intramural R&D expenditure (GERD - Gross domestic expenditure on R&D) (RDE1-5) indicates the source of funds for research and development within a region by sectors. This indicator determines the density of financial support with regard to R&D.
- The total R&D personnel and researchers (RDP1-15) indicator reflects individuals employed in the research and development field as well as researchers employed in the public or private sectors as academia. This indicator enables knowledge workers considered to be drivers of knowledge, innovation and facilitators of improvement to be identified.

5. **Technology:**

   "The successful adoption of the 4th industrial revolution will rely on the ability of governments, business and citizens to commit in supporting the transformation of society into a modern and smart society driven by advanced technology, skills, innovation and responsive policy" [71]. Technological diversification can promote regional innovation capability [83].

   To identify the technological readiness of regions, the equipment of businesses alone cannot determine the suitable environment for adapting and utilizing emerging technologies. A high degree of flexibility is essential to provide a basis for digital culture and skills [84].

   "Networking with external institutions highlights R&D collaboration of universities or public research institutions with industries, e.g., high-tech ventures or small-sized enterprises to foster technology convergence. Meanwhile, governmental supports can play a catalytic role in stimulating technology convergence networks" [85]. Spatial interconnections can be exploited by external parties such as universities, companies or the government, leading to an improved and competitive environment.

   In this regard, the technological factors affecting regional I4.0 readiness are the following:

- Employment in the technology and knowledge-intensive sectors (HTE1-8) can reflect the capability to adapt new technologies and the constant demand for modernization.
- The output of I4.0-related publications (PAP) indicates the intention to deal with modern-day technologies and future challenges.
- Patent applications (PAT) in the fields of Additive manufacturing technology, Nanotechnology, Machines or engines in general; Engine plants in general; Steam engines, Controlling; Regulating, Computing; Calculating, Counting, Signaling, and Information and Communication Technology (ICT) reflect the regional capability with regard to the adaption of new technologies.
- The indicator of Graduates in the fields of IT, Engineering or Mathematics (BSc, MSc, PhD) (GRA2-3) assumes the need for I4.0-related skills and graduates can be considered as the basis of knowledge transfer for an innovative technology-oriented environment.

3.3 Method of Industry 4.0+ readiness index construction and analysis

Based on the conceptual dimensions defined in the previous subsection, this part introduces the methodological workflow for constructing and analysing the regional Industry 4.0+ readiness index. The reader is guided through the process of selecting relevant data metrics and its analysis to derive an I4.0 and NUTS 2-specific indicator system capable of ranking regions according to their I4.0 readiness.

Figure 3.2 provides an outline of the methodological steps, which are individually discussed below:



FIGURE 3.2: The methodological workflow of developing and analysing the I4.0+ readiness index (Source: author's own work

1. **The determination of data sources and I4.0-related indicators to measure regional readiness**

   The following types of data sources were considered in terms of the development of a dataset for measuring the I4.0 readiness of NUTS 2 regions:

   (a) *Open governmental data:* Eurostat Regional statistics

   (b) *Alternative metrics:* Beyond open governmental data, reports and open data platforms were used in order to broaden the scope of examination in the field of I4.0. Table 3.1 shows the sources and connected indicators determined along with the spatio-temporal horizon.

   (c) *Media appearances:* The GDELT Project [86] makes it possible to overcome the spatio-temporal boundaries by media appearances. To precisely examine the appearance of I4.0-related news stories, we concentrated on four main topics, namely innovation, automation, research and development, and SMEs. In this regard, the following search words and areas were examined: Jobs, Competitive industry, Education skills development and labour market, Industry policy, Employability skills and jobs, Manufacturing

   Detailed descriptions of the identified variables are shown in Ref. [2] in S3 Appendix.Table 3.1 shows the analyzed reports and open data portals considered through the selection of possible indicators describing regional I4.0 readiness.

2. **Selection of I4.0-specific NUTS 2 regional indicators - the development of the I4.0+ readiness index**

   With regard to the previous step of identifying relevant data sources, this step concerns the selection of indicators able to describe regional readiness.

   The data selection occurred through expert sampling.

   As a final set of data sources, seven platforms are chosen and associated with the five dimensions of I4.0+ as follows:

   (a) Higher education and lifelong learning: Eurostat Regional statistics, ETER (European Tertiary Education Register), Erasmus+ Study Mobility Program, Global Research Identifier Database (GRID);

   (b) Labour market: Eurostat Regional statistics, Global Research Identifier Database (GRID), The GDELT Project

TABLE 3.1: Data sources and reports describing regional Industry 4.0 (Source: Ref. [2])

Source	Type	Examined indicator/data	Time horizon	Spatial horizon
Regional Innovation Scoreboard (RIS) [87]	Report	Innovative SMEs collaborating with others as a percentage of SMEs	NUTS 1 and 2 for different countries for CIS 2008, CIS 2010, CIS 2012, CIS 2014, CIS 2016	NUTS 1 and 2 for different countries for CIS 2008, CIS 2010, CIS 2012, CIS 2014, CIS 2016
Regional Competitiveness Index (RCI) [88]	Report	Knowledge workers (% of total employment)	average 2015-2017	NUTS 2
Cultural and Creative Cities Index (C3) [89]	Report	Average appearances in university rankings	2018	City
ETER [90]	Open data portal	Graduates in IT, Engineering and Mathematics (BSc, MSc, PhD)	2008-2016	NUTS 2
Erasmus+ [91]	Open data portal	Number of students participating in mobility programmes	2008-2013	NUTS 2
MA-Graph [92]	Open data portal	Publications by categories	2008-2018	NUTS 2
GRID [76]	Open data portal	Distribution of institutions by categories	-	NUTS 2
USPTO [93]	Open data portal	I4.0-related patent applications at the NUTS 2 level	2008-2018	NUTS 2
CORDIS [94]	Open data portal	Collaboration between organizations under Horizon 2020	2014-2020	NUTS 2

(c) Innovation activities: Eurostat Regional statistics, Microsoft Academic Graph (MA-Graph), United States Patent and Trademark Office (USPTO)

(d) Investment: Eurostat Regional statistics

(e) Technology: Eurostat Regional statistics, ETER (European Tertiary Education Register), United States Patent and Trademark Office (USPTO)

Regarding the expert sampling, 101 indicators were selected that describes NUTS 2 regional I4.0 readiness. A detailed description of the data describing the regional Industry 4.0 readiness index is found in the related work's Appendix S3 [2]. The initially compiled dataset comprised 414 alternatives (regions) and 101 criteria, grouped into five dimensions: higher education and lifelong learning, innovation, investment, the labour market, and technology. A detailed description of the dataset is provided in Ref. [95], while the original data, criteria definitions, and rankings are available through the following data repository: https://data.mendeley.com/datasets/23gwn43ygp/1. It should be noted that 34.11% of the original dataset consisted of missing values. For this reason, the dataset was carefully screened before analysis. Alternatives with outdated or invalid NUTS 2 codes, as well as those with at least 35% missing values, were excluded. In addition, criteria with at least 40% missing values were removed. As a result, the final dataset used in the

analysis consisted of 314 alternatives and 69 criteria. A brief description of the selected variables is provided in Ref. [96] S1 Appendix.

The I4.0+ indicator system is based on the five dimensions of regional development of I4.0 mentioned in Figure 3.1. The dimensions of the indicator system are weighted equally, to ensure transparency and reduce distortion. We must nore that there is a potential in defining weights for each dimension or indicator, however it requires further analysis.

3. **Determination of the ranking of NUTS 2 regions-based on their I4.0 readiness**

   The ranking of regions according to their I4.0 readiness is based on the following methods. The detailed mathematical description of the methods are discussed in Ref [21] in Appendix A-C and in the Methodology section of Ref. [96].

   (a) The *Promethee II* method [97] is applied to the indicator system that provides a pairwise comparison of the criteria. The *Promethee- GAIA* refers to a k-dimensional visualization of the set, which provides a more efficient representation. The ranking procedure was based on criterion-wise tied ranks. For each criterion, the positive rank-based flow was defined as the rank of the alternative, while the negative flow was calculated as the difference between the number of alternatives and the corresponding rank. The resulting net score was averaged across criteria, and the alternatives were ordered according to this mean net rank-based flow.

   (b) *Principal Component Analysis (PCA)* [98] provides a linear combination of the variables which is a widely used technique for data processing and dimensionality reduction. The biplot of PCA shows the alternatives, in this case, a two-dimensional space determined by the principal components.

   (c) Indicators were analyzed using the *Sum of Ranking Differences (SRD)* method [99] that compares variables based on the Manhattan distance between the sum ranked item differences in case the gold standard is fixed for the comparison. This method identifies and ranks indicators regarding their ability to describe the topic and reveal indicators ranked reverse. The results are visualized in two-dimensional space.

(d) *Promethee II-based Sum of Ranking Differences (P-SRD)* improves Promethee by evaluating the similarities between the criteria. In this case, the input matrix of SRD is the original data matrix of Promethee. The detailed description of the method is in Ref. [96].

4. **Validation of the results**

   As a result, an I4.0+ index is provided, which ranks regions regarding their I4.0 readiness. To validate the results, the correlation between the I4.0+ index and the economic (GDP), innovation (RII - Regional Innovation Index), and competitiveness (RCI - Regional Competitiveness Index) indexes is determined.

3.4 Results and Discussion

In this section, the proposed method is applied and analysed to European NUTS2 regions. The regional Industry 4.0 rank of regions is determined in Section 3.4.1, while the correlation analysis with economic, innovation, and competitiveness indexes are introduced in Section 3.4.2. Finally, the potential application areas of the I4.0+ index is proposed in Section 3.4.3.

3.4.1 Regional ranking based on I4.0 readiness

This section refers to the regional I4.0 readiness ranking methodology and the analysis of the given results. Indicators were analyzed using both the Sum of Ranking Differences (SRD) the Promethee II method, and the Promethee II-based SRD method. The ranking of regions is interpreted in a two-dimensional space based on the Principal Component Analysis (PCA) method.

Promethee II is a multicriteria decision aid method based on preference ranking organization, while the Promethee-Gaia method visualizes the set in a k-dimensional space [97]. SRD compares variables based on the Manhattan distance from the gold standard [99]. The similarities between the examined indicators were evaluated by the SRD method [99]. SRD is an effective way to analyze which indicators best describe our concept or are more backward and ranked in reverse. The PCA method is used to reduce dimensionality, and the ranking of alternatives (NUTS

2 regions) is presented in a two-dimensional space determined by the principal components (PCs). The principal components define which variables describing the topic the most (PCs are the linear combination of the variables).

The selected variables are shown in Figure 3.3 which reflects the main components describing I4.0 readiness. It is worth noting the two significant groupings, namely indicators connected to employment as well as the research and innovation-oriented indicators, which is also underlined by the P-SRD method.

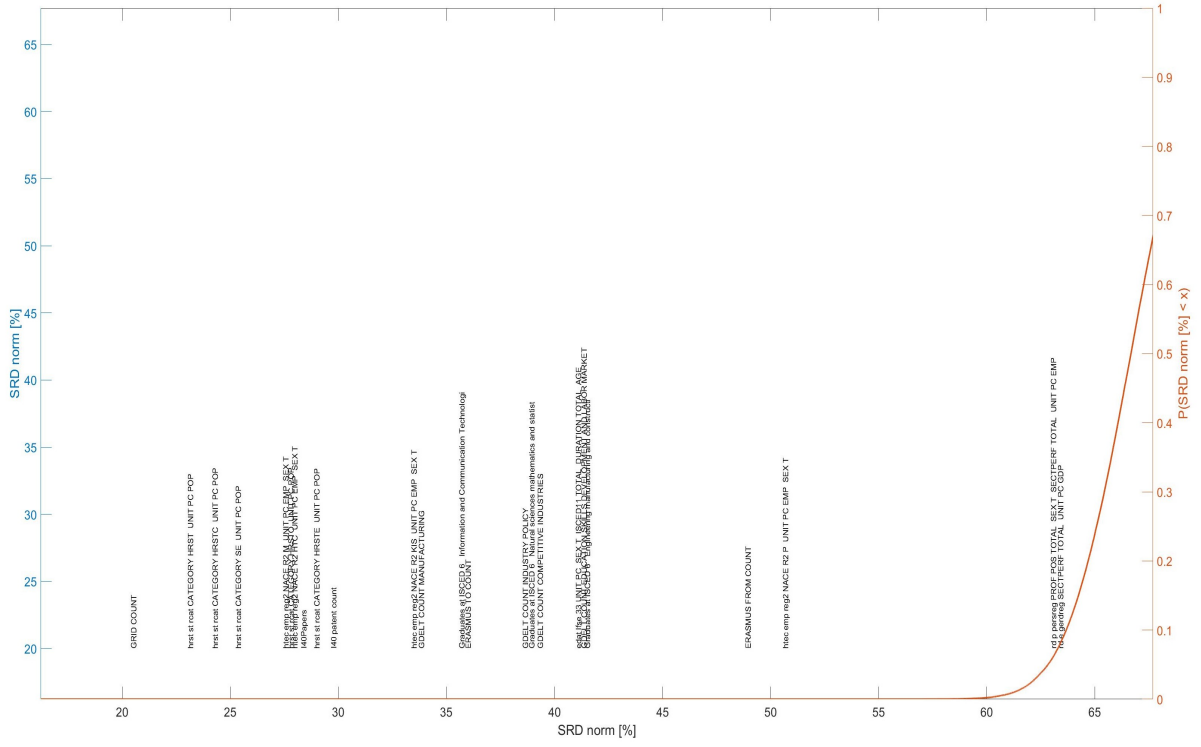


FIGURE 3.3: Selected variables from SRD according to their relevance in measurement (Source: Ref. [2]) (The descriptions of variables are shown in Ref. [2] S3 Appendix.)

The former indicates the importance and connection between education and innovation as there is an increasing need for a qualified workforce and scientific activities.

1. Total Employment rates of young people not in education and training (EMP30): This includes all educational levels and education between the ages of 15 and 34. It measures the number of people employed after finishing their education and categorizes them according to the years passed since completing their highest level of education.

The analysis of this indicator concerning the complex nature of employability and job opportunities can be a first step to reflect how difficult it is to get a job (measured in years). It reflects the development stage of an economy. We can assume where the employment rates of young people are higher (after finishing their education less then 2-5 years), job opportunities exist and economic value is generated in a region which fosters adaptation capability. However, it must be noted that other factors also shape this aspect.

2. The number of graduates in I4.0-related fields (GRA1, GRA2, GRA3): The I4.0-related educational programmes which are in demand that foster students (future workforce) to build an innovative mindset and gain I4.0-relevant skill sets.

   It should be noted that the Number of students participating in mobility programmes in the field (ERA2) is closely related to graduates.

3. The number of news concerning 'competitive industries' (GDC1), and 'education skills development and labour market' (GDC2) also appears. The number of news stories found can be considered to be a soft indicator for measuring the public awareness of the field, which can further be analyzed with regard to the tone of the news (attitude towards the events; whether it is positive, negative or neutral).

The second significant group is the research and innovation area, which correlates with labour, educational and technological factors. This is underlined by indicators concerning people employed in science and technology as well as the employment rate in the high-technology sector. Furthermore, investment also plays a significant role in the research and innovation area.

4. Human Resources in Science and Technology under the category of Persons employed in science and technology (HRS7) is the following indicator which is the closest to measure excellence in the field. It measures the percentage of the total population employed in science and technology as well as reflects the emerging need for researchers and scientific actions.

5. The density of research institutions (GRC) is another relevant variable, as it measures the number of institutions involved in research activities.

6. Human Resources in Science and Technology in the category of Scientists and engineers. As has previously been mentioned, the employment rate in science and technology plays an essential role in terms of development. This indicator is one of its sub-indicators, so its relevance is highlighted even more.

7. Employment in High-technology sectors (high-technology manufacturing and knowledge-intensive high-technology services) (HTE4, HTE7) measures people employed in this field as a percentage of the total employment. It indicates the demand of the labour market in the field, reflecting how regions keep up with advanced technologies.

8. Industry 4.0-related publications (PAP) are also heading in the direction of research activities and indicate regional maturity with regard to how much a given region is involved in I4.0 (research) projects.

9. Industry 4.0-related patent applications (PAT) approximate the direction of the Human resources in science and technology indicator. It is unequivocal that they are strongly correlated as those employed in science and technology are the reason for the density of patent applications (effects) within a region. This indicator can identify the research activities and innovation capabilities of a region.

10. The appearance of Industry 4.0-related news is located over one-third of the scale as is the case quite close to the reference. I4.0-related media appearances can from one hand qualify the events that have occurred in the relevant field, but on the other hand PR activities influence the number of news stories that occur in a region.

    It is fascinating that Intramural R&D expenditures (GERD) are located on the same scale as news appearances. Consequently, we can claim that GDELT can function as a "proxy" indicator and assume how much is spent on research and development actions in each sector. Furthermore, it should be noted that according to the Eurostat database, the latest available data on GERD when the analysis occured was from 2016, while the available news in GDELT is continuously updated.

    On the other hand, while the number of news has a significant effect, its tone does not provide added value for the index.

Figure 3.4 shows the ranking according to the Promethee method [97], as it makes a pairwise comparison according to the criteria and creates the full or partial ranking of alternatives. Visualization takes place by Promethee-Gaia method, while the ranking of variables is interpreted by the Principal Component Analysis of decision-making processes (preferences) calculated by criteria. Likewise, indicators that point the furthest, in the same way, are the most determinative.

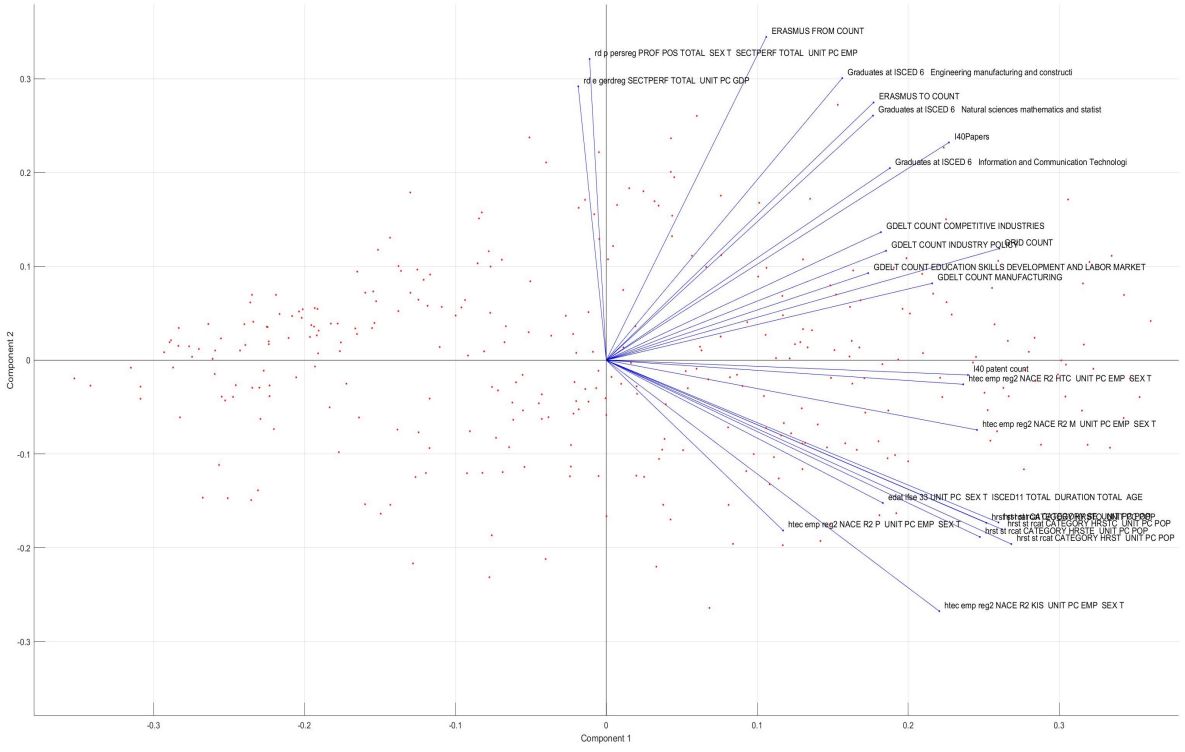


FIGURE 3.4: Selected factors according to their importance measured by Promeethe-GAIA (Source: Ref. [2])

The presented results underline the outcome of the SRD method, which categorized the two leading groups of indicators as (1) employment and (2) research and innovation actions. In this case, these factors are the Human Resources in Science and Technology (HRST), Total Employment rates of young people not in education and training (EMP), Employment in technology and knowledge-intensive sectors (HTE) and the Total R&D personnel and researchers (RDP).

The results of the P-SRD method shown in Figure 3.5. The SRD method is applied on the Promethee-based criterion net flow matrix to qualify the consistency of the criteria. Figure 3.5 shows the rank of criteria based on the P-SRD method. Criteria belong to the same criterion group are located on the same level on the y axis, while the x axis indicates the SRD values. The higher a criterion is located on the x axis

(closer to 0), the more determinative it is. In this case, the most determinative criteria are the sub-criterion of 'Human Resources in Science and Technology, which defines the percentage of people employed in science and technology (HS5), and/or people in tertiary education (HS7) as well as scientists and engineers (HS9). This sub-criterion is closely followed by the sub-criteria of 'Employment rates of young people not in education and training' (EM), the Number of research-related institutions' (GRC), the 'Number of patent applications in the relevant field by regions' (PT), and 'Employment in technology and knowledge-intensive sectors' (HT).

It is notable, that the first criteria is ranked around the SRD value of 20, which means more suitable criteria (which rank closer to the reference) could be found to determine regional Industry 4.0 readiness.

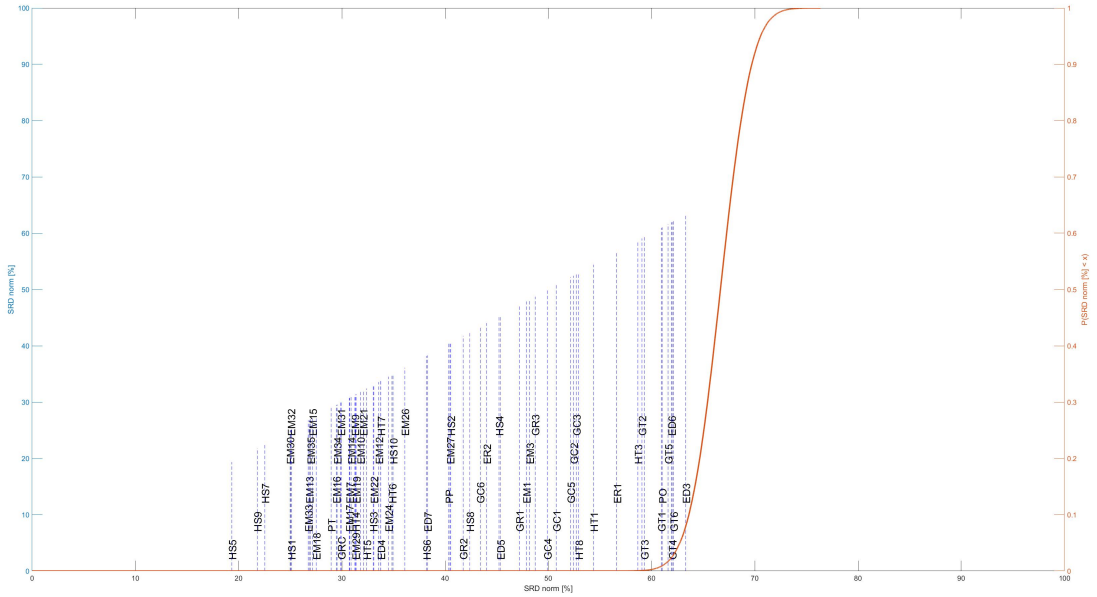


FIGURE 3.5: The rank of criteria according to the P-SRD method. The x axis shows the SRD values. Criteria belonging to the same criterion group are located on the same level on the y axis.(Source: Ref. [2])

After analyzing the indicators, the ranking of regions is presented in a two-dimensional space, based on Principal Component Analysis (PCA). The horizontal axis refers to regional development, while the vertical axis concerns the innovativeness of the given region. This visual interpretation can be seen in Figure 3.6. The more developed regions are located on a Pareto chart.

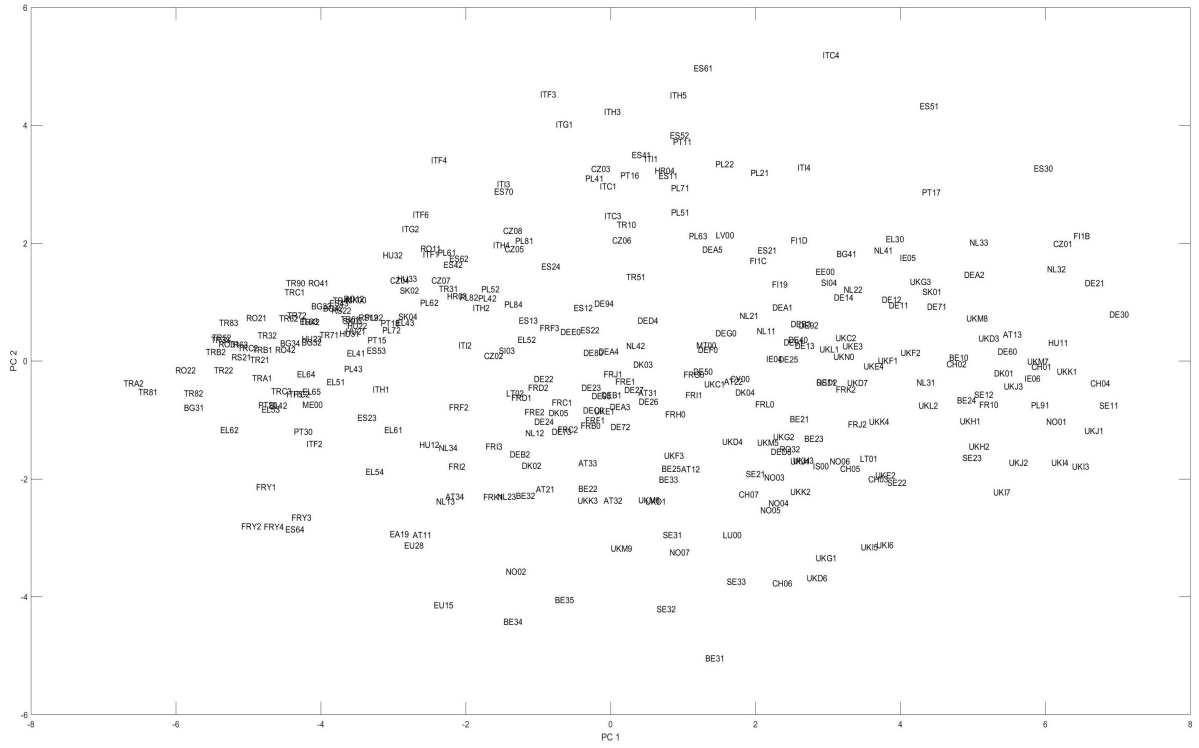


FIGURE 3.6: The layout of the regions according to the PCA method indicates regional readiness (Source: Ref. [2])

The developed ranking is visualized in a map presented in Figure 3.7.

According to the ranking, the most developed region is located in southern Finland, in the Helsinki-Uusimaa region to be exact, followed by the region of the capital city of the Czech Republic, that is, Prague and of Germany, namely Berlin.

The leading positions of these regions can be explained by their consistently strong performance in the most influential components of the I4.0+ readiness index, particularly in science and technology-related human resources, employment in high-technology and knowledge-intensive sectors, research capacity, and technology-related outputs.

Helsinki-Uusimaa shows the most balanced high-level performance across the principal readiness dimensions. It belongs to approximately the top 3% of the analysed regions in terms of total human resources in science and technology and to the top 2% in terms of core science and technology human resources and the proportion of scientists and engineers. The region is also among the European leaders in high-technology manufacturing and knowledge-intensive high-technology services employment. Its particularly strong investment and innovation profile is reflected

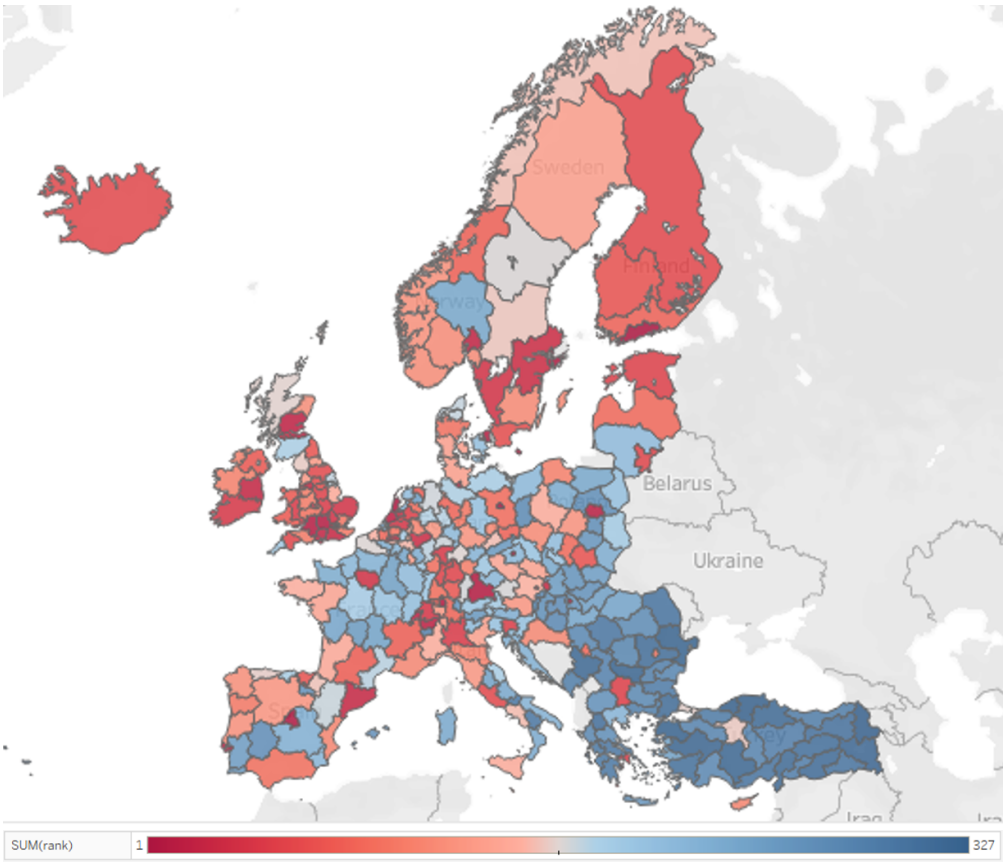


FIGURE 3.7: European NUTS 2 regional I4.0 readiness ranking based on the Promethee method (Source: Ref. [2])

in total intramural RD expenditure of 3.45% of GDP, the second-highest available value in the dataset, as well as its high concentration of R&D personnel and Industry 4.0-related patent activity. These mutually reinforcing strengths explain why Helsinki-Uusimaa occupies the first position rather than relying on a single outstanding indicator.

Prague's second position is primarily supported by its dense research and knowledge ecosystem, highly qualified labour force, and strong technology-oriented employment structure. Prague has one of the highest concentrations of research institutions in the dataset and the highest observed government-sector R&D personnel intensity. It is also among the top-performing regions in high-technology manufacturing, knowledge-intensive high-technology services, science and technology-related human resources, and tertiary educational attainment. Its Industry 4.0-related patent count is less dominant than that of Helsinki-Uusimaa; consequently, Prague's position is better explained by the concentration of research institutions, public research capacity, skilled human resources, and technology-intensive employment than by patent output alone.

Berlin also demonstrates a broad science-, education-, and innovation-oriented profile. Its strengths include a high concentration of research institutions, a large number of Industry 4.0-related scientific publications, substantial numbers of ICT and engineering graduates, and a high proportion of employees in science and technology and in technology- and knowledge-intensive sectors. Berlin therefore performs particularly strongly in the higher-education, research-institutional, human-capital, and scientific-output components of the index. However, several regional R&D expenditure and R&D personnel indicators are missing for Berlin in the underlying dataset; thus, its high position should not be attributed directly to those variables. Based on the available indicators, Berlin's ranking is primarily supported by its research infrastructure, scientific output, graduate base, and technology-oriented labour market.

Figure 3.8 presents a country-level aggregation of the regional I4.0+ ranking. It is important to emphasize that the values shown in the figure do not represent the results of a separate national-level readiness assessment. For each country, the arithmetic mean of the PROMETHEE II rank positions of all NUTS-2 regions belonging to that country was calculated.

Since rank position 1 represents the best-performing region, a lower country-average rank indicates a generally more favourable regional I4.0+ readiness profile. Based on this unweighted aggregation, Ireland has the lowest average regional rank (55.00), closely followed by Finland (55.25), Iceland (57.00), Estonia (58.00), and Switzerland (66.57). Finland's favourable country-level result is consistent with Helsinki-Uusimaa's first position, but the national value also incorporates the ranks of Finland's other NUTS-2 regions. Consequently, the country-level order may differ considerably from the ranking of individual leading regions.

The figure should therefore be interpreted as a summary of the relative rank positions of the regions within each country rather than as a cardinal measure of national Industry 4.0 readiness. The calculation is not weighted by regional population, economic output, or territorial area; each NUTS-2 region contributes equally to the country average. Moreover, comparisons should take account of differences in the number of NUTS-2 regions. Countries represented by a single region, such as Iceland or Estonia in the analysed dataset, inherit that region's rank directly, whereas countries with numerous and heterogeneous regions are represented by an average that may conceal substantial within-country disparities.

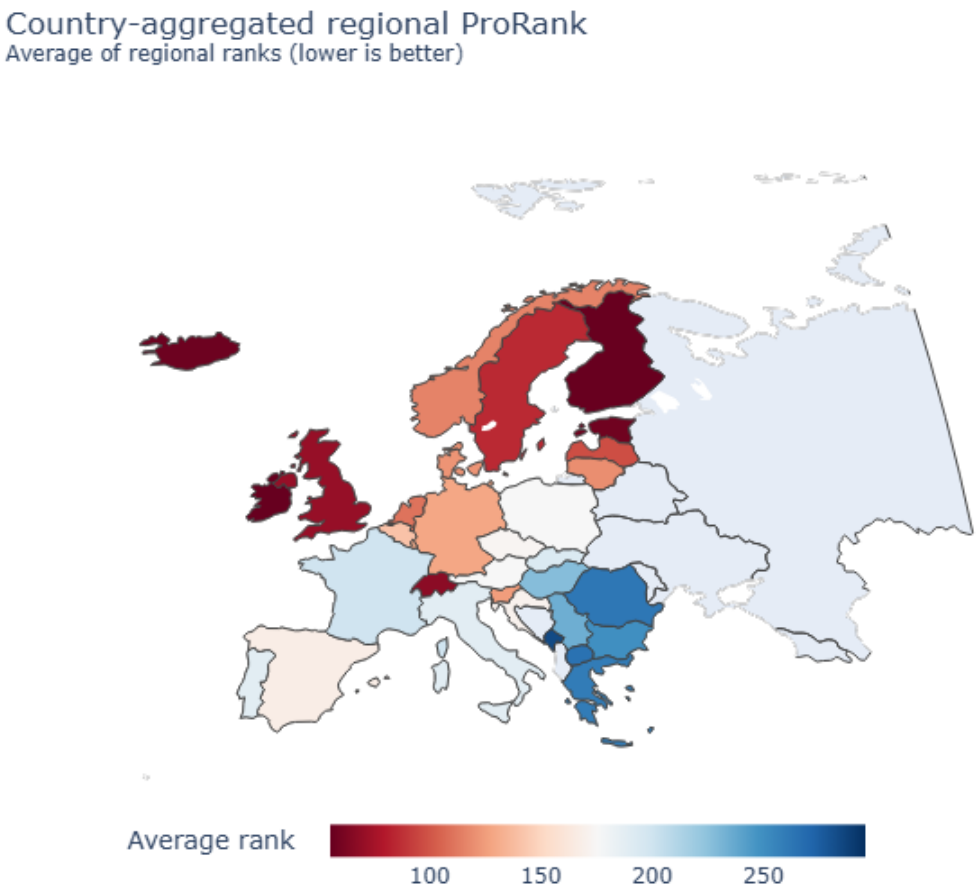


FIGURE 3.8: Country-level aggregation of the European NUTS-2 regional I4.0+ readiness ranking. Country values represent the unweighted arithmetic mean of the PROMETHEE II rank positions of the NUTS-2 regions belonging to each country; lower average ranks indicate more favourable readiness profiles. (Source: author's own work.)

3.4.2 Correlation analysis of the I4.0+ and economic, innovation and competitiveness indexes

In this section, in order to provide a realistic and more in-depth picture, we compare our index with economic-related indicators, and existing indexes which aimed to rank regions according to innovation capability and competitiveness.

1. Comparing the I4.0+ index with GDP is essential to identify the relationship between European regional economic growth and the regional I4.0 ranking based on the Promethee method. The results indicate a correlation of 0.68,

which proves the connection between economic development and our proposed methodology.

It should be noted that other factors influence GDP as well so, in this regard, it is hard to identify the developing effect ofI4.0 on economic growth. Figure 3.9 underlines the fact that there are regions with relatively high GDPs compared to our index, as their economic growth originates from factors other than the I4.0-related field.



FIGURE 3.9: Correlation between GDP and our I4.0+ ranking system (r^2 = 0.68)(*Source* : *Ref.*[2])

2. The relationship between the real growth rate of regional gross value added (GVA) and the proposed I4.0+ readiness index should be interpreted

with caution, as the two indicators capture different aspects of regional development. GVA growth reflects short-term economic dynamics, while the I4.0+ index measures structural readiness for Industry 4.0 transformation, including skills, innovation capacity, technological preparedness, investment, and labour-market conditions. Thus, regions with lower I4.0+ readiness may still achieve high GVA growth due to catching-up effects, public or private investment, sectoral restructuring, or external industrial expansion. However, such growth does not necessarily indicate long-term innovation- and technology-based competitiveness.

3. According to the Regional Innovation Scoreboard 2019 (RIS) report, its composite indicator Regional Innovation Index (RII), which is used to measure the average innovation performance, is also correlated with the proposed index.

   Figure 3.10 shows a correlation of 0.70, which clearly represents the similarity. The horizontal axis refers to the innovation feature, while the vertical one concerns the specific features of I4.0. It nicely represents that for regions considered to be moderate innovators, in order to advance to the next level, the governmental focus is firmly on the development of innovation and the application of the I4.0 concept. These regions are located above the diagonal.

4. The Regional Competitiveness Index is also a core indicator that needs to be correlated, as competitiveness provides a stable foundation of which to apply the I4.0 concept. By comparing the two indexes, a correlation of 0.70 was calculated. It is worth noting that there are regions where I4.0 is not a priority, even though they still belong to the competitive regions such as regions of AT and LU.

In conclusion, the proposed I4.0+ index can determine regional development and innovation capability (can be one of its factors).

3.4.3 Application areas of the proposed I4.0+ index

Identifying the stakeholders and the applicability of the proposed index is critical as the possible future demand and interest must be considered. The application value of the proposed I4.0+ index goes beyond descriptive regional benchmarking.

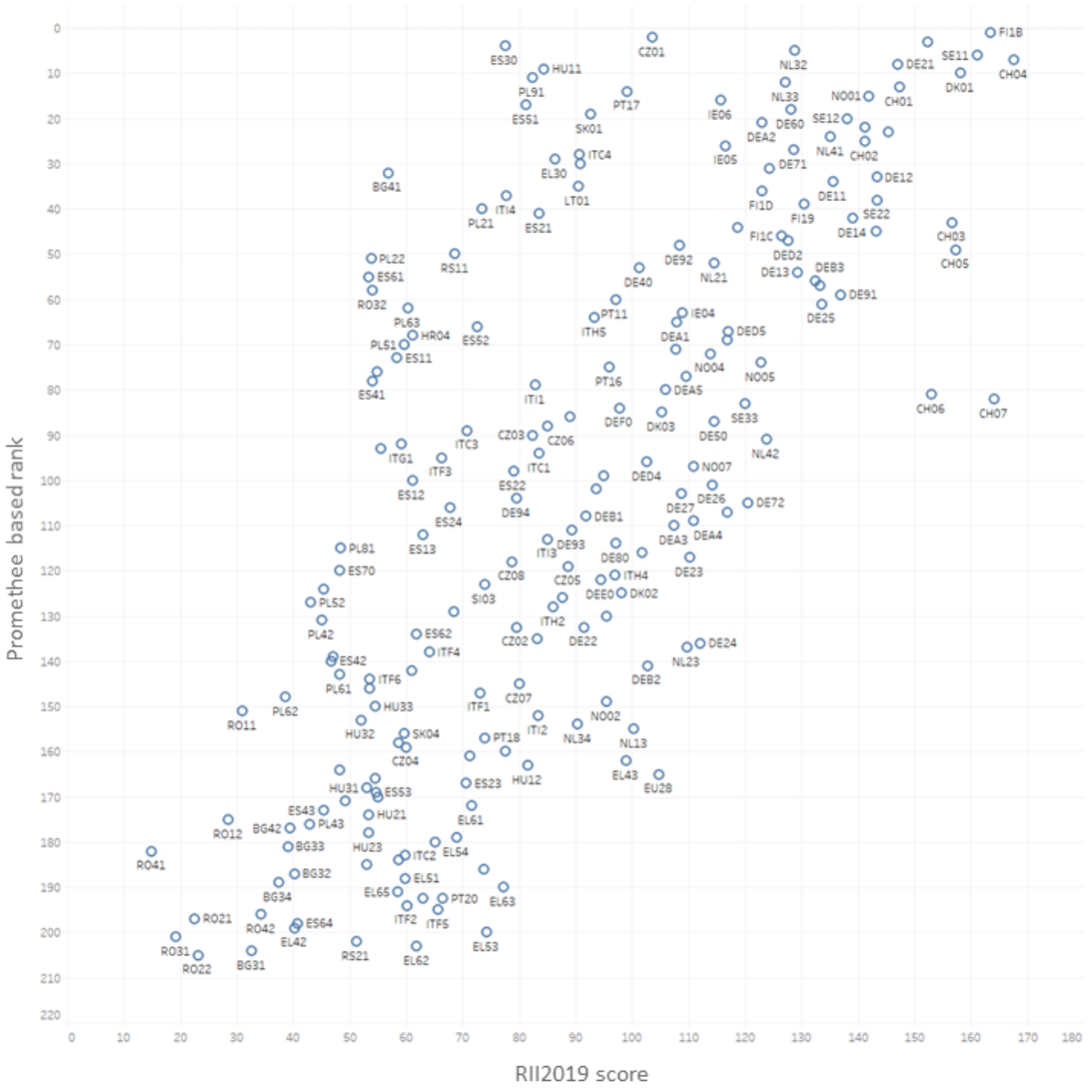


FIGURE 3.10: Correlation between the proposed I4.0+ ranking index and the Regional Innovation Index (RII) ($r^2 = 0.70$)(*Source* : *Ref.*[2])

Its main benefit lies in supporting differentiated interventions by showing not only which regions perform better or worse overall, but also which structural dimensions are responsible for these differences. Therefore, the index can be used both as a comparative assessment tool and as a diagnostic instrument for identifying development bottlenecks and intervention priorities.

From a practical perspective, the results can be utilized at multiple decision levels. Four possible parties are classified, which are shown in Figure 3.11, who could benefit from utilizing the I4.0+ regional readiness index and conclude the regional development status.

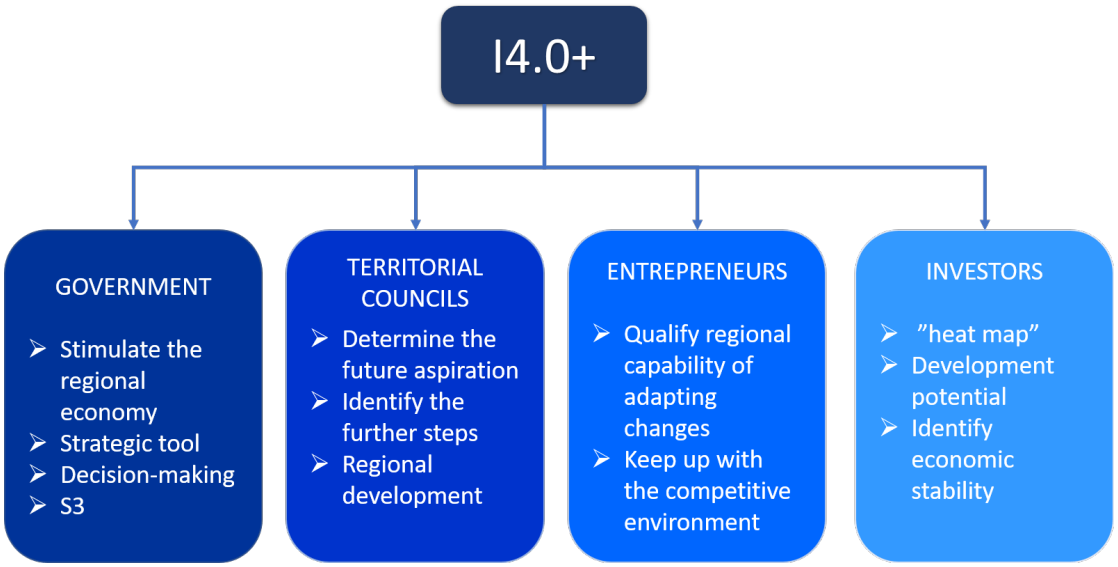


FIGURE 3.11: Possible areas of application of the I4.0+ index to utilize the potential in terms of regional strength (Source: Ref. [2])

1. Governments have power over regions not just financially but in terms of policy-making processes as well. By considering regional economic development, governments can use this index to measure regional statuses and identify future strategic plans for their improvement. This can include research-and-development allocations, innovation projects and Smart Specialization Strategies (S3) between regions. If a country wants to make its mark on the "global world map" it has to start developing from lower levels and keep up with continually changing global requirements.

2. The role of territorial councils is also appreciated as they are directly involved and enable to identify what has to be improve. The I4.0+ readiness index confirms the position of regions in the ranking. Regions can determine their future aspirations and further steps in order to be competitive regionally and strong economically. The innovation-helix is performed in the regional stage and can create connections between businesses, governments and academia.

3. Entrepreneurs connected to the business sector can use the index as a tool for identifying the capability of regions to remain or become stable. They can look into which regions are worth investing in and how regions can develop by the concept of I4.0. The connection of enterprises to this concept is critical as they can function as the potential drivers of economic growth.

4. Investors can use the proposed indicator system as a "heat map" to determine which region(s) is worth investing in, or stable enough to cope with future challenges. The area of investment is critical in terms of research and development, manufacturing or attracting businesses to a region.

3.5 Conclusion

This chapter aims to provide an accessible tool for strategic planning and monitoring that regional stakeholders can utilize. The created concept can facilitate the understanding of the current status of regions according to their I4.0 relation and can contribute to elaborate medium-term development roadmap. For these reasons, a regional I4.0-specific indicator system was created, which makes the concept measurable and applicable. Indicators are categorized into five groups that support areas in favour of regional I4.0 readiness namely higher education and lifelong learning, the labour market, innovation, investment and technology. All segments have their specific scope, although in the Triple Helix, the actors/segments amplify their effect and increase the development and innovative features of regions by cross-collaborating actions. We must note that there is a great future research potential in expanding the model for the quadruple helix concept, which includes the societal aspect as well. According to the spatio-temporal coverage, the desired data availability is the NUTS 2 regional level, and as recent as possible. Bearing in mind the purpose of measuring I4.0 readiness, the selection of indicators was strongly dependent on their specific relation to the area, e.g. I4.0-related publications, patents or educational training appearances. Moreover, the appearance of I4.0-related news stories was measured at the regional level and used as a "proxy" indicator to identify the regional connection to the field.

An I4.0+ composite indicator was generated from the aforementioned group of indicators and applied to the regions of the European Union. The importance of the employment factor and innovation activities as highlighted according to both the SRD and Promethee methods of ranking regions. The most advanced region is the Helsinki-Uusimaa region in Finland, followed by the capital city of the Czech Republic, that is Prague and of Germany, namely Berlin region.

The relevance of the index emphasized by the results of the correlations with other indicators. With both economic growth (GDP, Change of GDP) and innovation

(RII), competitiveness (RCI) indexes approximates to correlation of 0.7. This similarity refers to the I4.0 fostering effect of innovation, competitiveness and economic development. However, it should be noted a comparison with an indicator that is independent of the proposed index would provide stronger evidence for its validity.

The untapped potential has also been revealed with regard to the application of the index as it can function as (1) a strategic governmental tool to stimulate the regional economy, (2) a decision-making tool of territorial councils to define in which field they should invest, (3) "heat map" for investors to determine which region has potential in terms of development and a stable economic environment, and (4) a tool for entrepreneurs to qualify the capability of regions to adapt to changes and remain competitive.

Beyond its standalone value, the regional perspective developed in this chapter occupies a bridging position within the overall multi-level framework of the dissertation. While the global level identifies broad sustainability and transformation-related patterns, attention shifts, and emerging priorities, the regional level translates these macro-level signals into territorially interpretable development capacities. In this sense, the I4.0+ readiness index serves as an intermediate decision-support layer: it helps explain where the structural conditions of the twin transition are more or less favorable, and where targeted intervention is needed to transform global strategic directions into realistic regional development pathways. At the same time, the national level should also be considered as an important mediating layer between global agendas and NUTS-2 regional implementation. National sustainability, digitalization and industrial policies, as well as legal requirements and funding schemes, can strongly shape regional development priorities and the opportunities available for organizational transformation.

At the same time, the regional level also connects directly to the organizational and process levels discussed in the following chapters. Organizations do not adopt Industry 4.0 and 5.0 solutions in isolation, their technological, human, and innovation capacities are embedded in regional ecosystems shaped by skills, research intensity, institutional density, labor market structure, and investment conditions. Therefore, the regional readiness results help identify the contextual enablers and constraints under which organizational sustainability strategies and process-level

digital transformation efforts can be effectively implemented. In this way, the regional analysis does not merely describe territorial differences, but functions as a translational layer between global agendas and local execution.

The practical utilization potential of the results is also substantial. The proposed index can support evidence-based policy design, priority setting in regional innovation and smart specialization strategies, targeted capability development, and investment screening. It can also help distinguish whether a region should primarily strengthen its human capital base, innovation system, technological absorption capacity, or research and development intensity. Accordingly, the results are not only suitable for benchmarking, but also for diagnosing bottlenecks, designing differentiated intervention portfolios, and supporting the alignment of regional development policies with organizational and industrial transformation needs.

Therefore, in the context of the thesis, this chapter operationalises the regional dimension of the twin transition. The I4.0+ indicator system and the resulting regional readiness index directly support Thesis II and bridge the global perspective of Thesis I with the subsequent chapters that focus on Industry 4.0/5.0 at organisational and process level.

Chapter 4

Key factors of Industry 5.0-based organizational sustainability

Moving beyond global and regional perspectives, this chapter examines how Industry 5.0 becomes sustainably, human-centrically, and resiliently operational within organizations. It develops and applies a decision-support framework that links external sustainability expectations (SDGs and the GRI Topic Standards) with internal capability building across 18 Industry 5.0 solutions, complemented by Operator 4.0 and human-centric management principles. The chapter integrates quality function deployment (QFD) and network analysis to identify the interrelations between sustainability requirements and Industry 5.0 solutions and to identify key factors for prioritizing Industry 5.0-related organizational developments.

4.1 Introduction

Organizations have a crucial role to play in advancing sustainable development, and measuring and reporting on their impact is key to ensuring progress toward achieving Sustainable Development Goals (SDGs) [3]. However, organizations often struggle to determine what actions to take and how to implement effective strategies for sustainable development. Many lack the systematic guidance, tools, and methods needed to address complex sustainability challenges and integrate these into their operational and strategic frameworks. Without a structured approach, organizations risk inefficient resource allocation and missed opportunities

for impactful change. This chapter aims to address this gap by providing a comprehensive tool that offers a standardized framework, systematic methods, and a knowledge repository to support organizations in advancing sustainability efforts and aligning with the emerging Industry 5.0 (I5.0) principles. Industry 5.0 promotes resilient, human-centric, and sustainable operations, organizations must prioritize sustainable development and integrate them into their business models, products, and services [8]. To achieve sustainable development in Industry 5.0, organizations will need to embrace circular economy principles, reduce waste and emissions, promote renewable energy sources, ensure ethical, equitable, and resilient business practices, and focus on human-in-the-loop [8]. This requires a shift in organizational mindset and culture, where sustainability considerations are integrated into decision-making processes and become a core part of organizational strategy, where corporate social responsibility plays a vital role to support these activities [100]. Incorporating Environmental, Social, and Governance (ESG) principles is essential for this transformation, as these principles provide a comprehensive framework that aligns business practices with broader societal goals. ESG principles emphasize environmental responsibility, social equity, and robust governance structures, which are critical for ensuring that Industry 5.0 initiatives are sustainable and inclusive [101]. Digital technologies can support the transformation of manufacturing systems towards greater circularity and sustainability by enhancing data collection, analysis, and reporting capabilities, enabling organizations to make more informed and ethical decisions [102]. In this context, decision-making processes should rely on evidence-based and data-driven methods and techniques to achieve better resource allocation and efficiency [103].

Therefore, systematically measuring and reporting on sustainability impact is essential, as it will allow organizations to identify their maturity, track their progress and impact of the business decisions on the environment, society, and governance, aligned with sustainable development goals, identify areas for improvement, communicate their sustainability performance to stakeholders, and support benchmarking activities [100]. By prioritizing sustainability and embracing Industry 5.0 principles, organizations can contribute to a more sustainable future, and ensure that economic development is achieved in a way that is socially and environmentally responsible. To attain sustainability and conduct performance monitoring, an organization necessitates a *standardized management framework*, a *systematic method*, and a *knowledge repository*.

A standardized management framework provides guidance and structure for mapping progression towards sustainable requirements through Industry 5.0 principles. For this purpose, standard corporate reporting frameworks and the Industry 5.0 concept can be promising. Standard reporting frameworks have been considered such as GRI, SASB (Sustainability Accounting Standards Board), and TCFD (Task Force on Climate-related Financial Disclosures). Based on their general applicability and connection with ESG was one of the main aspect for the selection criteria. SASB is more financial focused and industry specific, and FCFD lacks of other sustainability aspect than climate change. Since GRI has standardized indicators across environmental, social, and governance (ESG) aspects and covers 70% of the indicators [104]. GRI Standards are providing guidelines for organizations to comprehend and document their effects on the economy, environment, and society in a consistent and trustworthy manner, thereby augmenting the transparency of its contribution toward sustainable development [24]. GRI reporting can be an effective method to assess the sustainable work of companies [105] and a significant number of companies use the GRI framework to disclose information on their ESG (Environmental, Social and Governance) activities [104]. While the Industry 5.0 European initiatives are laying the foundation for transitioning into a more resilient, human-centric, and sustainable organization through the support of integrated digital and technological innovation [106]. Organizations should be analyzed through systematic methods integrating these principles and frameworks.

Therefore, there is a need for a systematic method that guides through the process of efficiently defining sustainability requirements and supporting Industry 5.0 solutions, as well as their relationships. For this purpose, the quality function deployment (QFD) method is a promising tool as despite being a quality management standardized method [107], quality function deployment enables the identification and quantification of interrelationships and cross-correlations among sustainability requirements and Industry 5.0 solutions, as well as within Industry 5.0. Moreover, comprehending the synergistic effects of the solutions (e.g., through digital transformation tools, enabling technologies, etc.) and how investments in Industry 5.0 solutions facilitate sustainable development and reporting activities within the ESG framework [108] is critical. QFD is said to be an excellent tool for developing organizational processes and supports cultural change and management [109]. The QFD method and its extensions have found extensive application in studies related to sustainability, particularly in facilitating decision-making processes. For example in product design [110], such as for household water treatment system

design [111], product-service design [112], identification of organizational sustainability factors [27] in specific sectors e.g. energy [113], shipping industry [114], bioenergy industry [115], among others. QFD has been proved to be an efficient tool to analyse complex interactions, such as identifying relationships between sustainability supply chain risks, supply chain resilience and Industry 5.0 drivers [116]. However, these studies reveal the potential in identifying key factors of organizational sustainability design and development, the identified indicators are mostly self-defined and generic, lacking systematic indicators to measure organizational performance. Hence, the adoption of a methodical framework involving the GRI Standard is proposed. While there have been analyses of the QFD method and GRI indicators using a performance prism based on concurrent engineering and a developed balanced scorecard, the focus of such analyses has been primarily on economic indicators [117]. Thereby, a comprehensive model utilizing multiple aspects of GRI Topic Standards and indicators that measure organizational performance is needed. In addition to assessing organizational performance, a comprehensive overview of tools and methodologies that facilitate the development of organizational sustainability and promote progress toward Industry 5.0 has considerable potential.

An open knowledge repository that includes best practices, tools, and methods for organizations to achieve sustainable requirements has great value and can be further expanded as the field continues to evolve and develop. Open knowledge repositories can provide easy and free access for all, can facilitate knowledge-sharing among organizations, researchers, decision-makers, and other parties, promote innovation, transparency and contribute to the democratization of knowledge [118] and support the "leave no one behind" concept of sustainability [119].

Based on the three fundamental aspects, a quality function deployment (QFD) and network analysis-based framework is proposed to identify key factors for prioritizing Industry 5.0-related organizational development. The methodology involved a thorough review and restructuring of evaluation systems to establish a structured decision-support framework. QFD has been chosen due to its interpretability and adaptability for dynamic development processes, which have been proved to be efficient. This approach proved operationally viable, particularly for defining priorities within design-focused contexts. Due to the structure of QFD, it ensure that Industry 5.0 developments directly address sustainability challenges by systematically mapping requirements to solutions. However, since the requirements are

interlinked, but the QFD cannot reveal those interconnections in a highly extended case. In order to consider the hidden relationships and critical points, network analysis have been utilized. Network analysis can provide higher level information about the dependencies and interconnections between sustainable development goals, requirements and Industry 5.0 solutions.

The sustainability requirements are based on the Global Reporting Initiatives Topic Standards, which are pre-associated with the corresponding SDG targets and reporting requirements [120], thereby enabling the assessment of the solutions' effect on sustainable development. To allocate the sustainability requirements and indicators to Industry 5.0 solutions, the utilization of the QFD method is suggested. By doing so we are able to identify which sustainability requirements can be supported and developed via which Industry 5.0 solutions, as well as enable us to quantify which solutions are key factors in improving organizational performance on sustainability aspects. The relationships that have been identified are founded upon a thorough analysis of existing literature, documented best practices, readiness models, and European initiatives promoting the progression toward Industry 5.0.

The proposed framework is built upon 17 SDG goals, 61 SDG targets, 141 sustainability requirements (GRI Topic Standards), 18 Industry 5.0 solutions. The applicability of the method is demonstrated through an illustrative study for key relationship exploration that is a partial exploration since each organization must customize the method based on their portfolio. It should be noted that the examples under consideration are not fully exhaustive, as the requirements and solutions are continually expanding through the incorporation of novel aspects and methodologies, as well as the customization of the variables can include organization-specific strategic and key performance indicators.

Therefore, the contribution and the structure of the chapter are as follows:

- In Section 4.2, by following the proposed systematic development cycle, organizations can integrate ESG considerations into Industry 5.0 strategy formulation, investment selection, operational design, performance management, and continuous improvement. Measurement and reporting are treated as feedback and accountability mechanisms within this broader cycle, rather than as its primary purpose.

- In Section 4.3, the method of the QFD and network analysis-based identification of the key factors of Industry 5.0 solutions is discussed.
- Section 4.4 introduces the applicability and utilization potential of the proposed framework through a partial exploration study to identify key relationships. This section discusses each part of the QFD-based assessment in detail.

The proposed methodology development holds significant potential for organizations to identify opportunities related to sustainability within the context of Industry 5.0. Furthermore, it can aid decision-making processes related to investment in Industry 5.0 solutions and their impact on organizational performance as measured by the SDGs. By providing a structured approach to mapping key relationships between sustainability requirements and technological solutions, the methodology empowers organizations to pinpoint critical areas for improvement, align their strategies with global sustainability goals, and enhance operational efficiency. Additionally, the framework's adaptability ensures that it remains relevant across diverse industries and organizational contexts, enabling tailored applications that reflect specific goals, challenges, and priorities. As a result, organizations can use the methodology not only to optimize their sustainability strategies but also to strengthen their competitive advantage and long-term resilience in the face of evolving industry demands and global sustainability requirements.

4.2 Development cycle of sustainability-oriented Industry 5.0 strategy making and reporting

By following the proposed systematic development cycle, organizations can ensure that their Industry 5.0 efforts are aligned with sustainable development goals and that they are tracking and reporting on their progress toward these goals and driving long-term sustainability performance.

The sustainability-oriented steps of organizational Industry 5.0 strategy development and reporting are shown in Figure 4.1. The concept is partly based on the GRI concept [3], which outlines a three-step process to integrate the SDGs in existing business and reporting processes. The concept has been explicated and extended in the context of Industry 5.0.

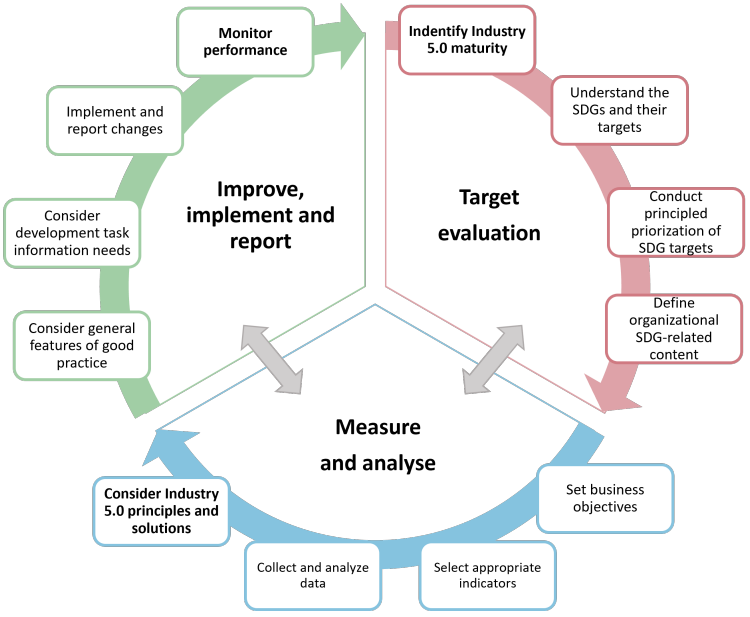


FIGURE 4.1: Sustainability-oriented steps of organizational Industry 5.0 strategy development and reporting based on Ref. [3] (Source: Ref. [4])

During the target evaluation stage, it is essential that organizations gain a comprehensive understanding of their environmental requirements, ongoing initiatives, and current developmental stage to establish a baseline for their developmental project. In this regard, identifying the key factors of organizational performance in Industry 5.0, including sustainability, human-centricity, and resilience, as well as the current stage for digital technologies and data-driven solutions, facilitates identifying the areas in which an organization needs to evolve and focus its strategy. Furthermore, with respect to sustainability, comprehending the SDGs and their corresponding targets and indicators in the context of the organization's social, economic, and environmental benefits is crucial for informed decision-making. Based on this information, organizations can prioritize the targets and areas in which they aim to make an impact and potentially invest in. The prioritization of efficient performance towards achieving SDGs by implementing digital technologies and Industry 5.0 approaches aims to enhance productivity and economic benefits through the reduction of waste and environmental impact in industrial processes, and the implementation of cleaner production practices and sustainable manufacturing [121]. Such sustainable practices can lead to financial benefits, such as cost savings through optimized processes, reduced waste, and energy, and increased efficiency [122]. Additionally, it can lead to enhanced reputation among customers and investors, thereby fostering brand loyalty [123].

In the measure and analyze stage, organizations are required to establish their business objectives, select appropriate performance indicators, and undertake a comprehensive analysis of their performance. The chosen indicators must be evaluated within the context of Industry 5.0 while developing a strategic developmental plan. In this regard, our proposed methodology provides an excellent base pairing sustainability indicators with Industry 5.0 solutions and calculates which solutions a given organization should focus on/invest in based on their set preferences and additional capacity constraints.

4.3 QFD and network analysis-based method for the indication of key factors of Industry 5.0 solutions

In order to support Industry 5.0 strategy-making, our proposed method can be integrated into the model development practices to identify the relationship between sustainability requirements and Industry 5.0 solutions. For this purpose, the foundation of the quality function deployment method is utilized.

Figure 4.2 indicates the schematic representation of the quality function deployment-based structure and assessment of supporting the development of organizational sustainability.

The QFD for organizational sustainable development is built as follows:

- The 17 sustainable development goals and the related indicators have been connected to the sustainability requirements based on the Global Reporting Initiatives report on linking the SDGs and the GRI Standards [120]. This rendering contains 61 SDG targets and 141 GRI Topical Standard.
- The sustainability requirements are gathered based on the GRI Topics [120]. Let GRI_i be a set of sustainability requirements. Each GRI_i is weighted with λ_i, $i = 1, ..., n$. The selection of weights can be determined according to the organizational preference, specifically, the sustainability requirements that are targeted for emphasis.

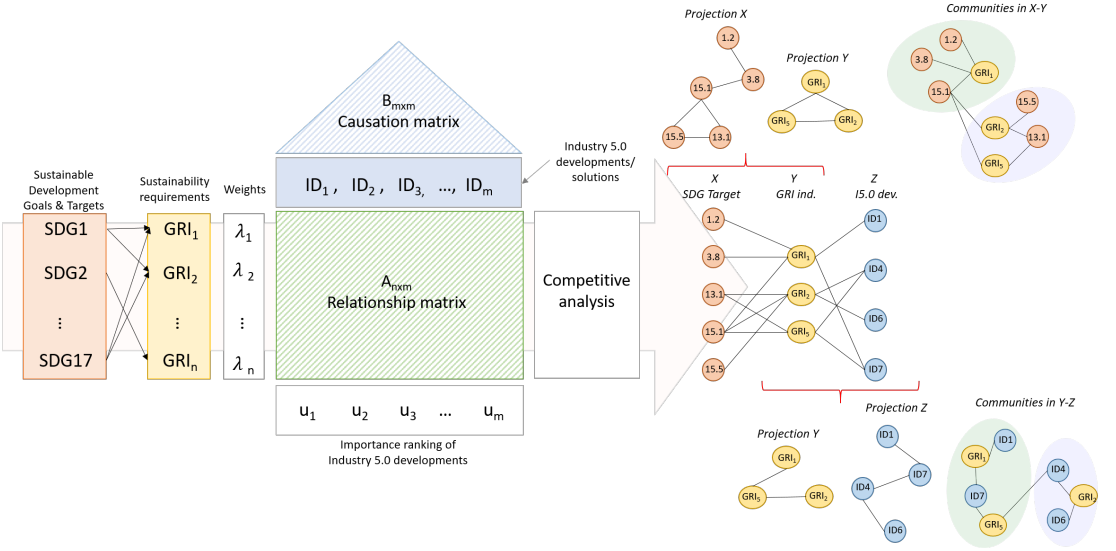


FIGURE 4.2: Schematic structural representation of quality function deployment for organizational sustainable development. (Source: Ref. [4])

- Industry 5.0 solutions are identified by the work Ghobakhloo *et. al.* [103], which however covers organizational, system, functional and managerial level soltuion, but the human-in-the-loop aspects seems to be missing. Therefore, the solutions have been extended with the concept of Operator 4.0 [124] and Human-centric approach. The former represents the functional and technological field on the shop floor, the latter the managerial and strategic aspects of providing foundations to the developments. The identified 18 solutions are represented by ID_j, where $j = 1, ..., m$ is the j-th solution.

- The relation of the sustainability requirements and I5.0 solutions form an $n \times m$ matrix A. $a_{i,j} \quad (i \in GRI, j \in ID) = 1$ if there is a relationship between the i-th sustainability requirement and j-th I5.0 solution, 0 otherwise.

- The relationship of the defined I5.0 solutions is explored in an $m \times m$ B matrix, where $b_{j,k}$ highlights how would the change in solution j effect solution k. These interlinkages are based on the work of Ghobakhloo *et. al* [103]. Note, that $b_{j,k} \neq b_{k,j}$ and $b_{jj} = 1$. We assume the synergies between I5.0 solutions have a one-way causal effect. If $b_{j,k} = 1$, then b_j tend to directly case b_k. In case $b_{j,k} = 1^*$, where the "*" indicates that b_j indirectly have a causation effect on b_k through other I5.0 solutions.

- The importance ranking value of the I5.0 solutions is calculated as $u_j = \sum_{j \in ID} \lambda_i a_{i,j} \quad \forall i \in GRI$, where u_j is the importance rank of the j-th Industry 5.0 solution, and $j = 1, ..., m$.

  The importance ranking aims to provide an outline of how much Industry 5.0 solutions tend to influence the selected sustainability requirements and which solutions should the organization focus on developing. The greater the value of u_j, the Industry 5.0 solution is more important on the sustainability requirements. If the u_j is high, it either occurs affects important sustainability requirements (with high λ value) or happens to be in a relationship with several sustainability requirements. Lets take an example on the below example matrix: , where ID_1 Industry 5.0 solution is ranked the most important since it has the most connection and the weights do not differ.

SDG	GRI	Weight	ID_1	ID_2	ID_j
SDG1	GRI_1	$\lambda_1 = 1$	$a_{11} = 1$		
SDG1	GRI_2	$\lambda_2 = 1$	$a_{21} = 1$	a_{22}=1	
SDG2	GRI_3	$\lambda_i = 1$			a_{ij}=1
			u_1= λ_1*$\mathbf{a}_{11}$+ λ_2*$\mathbf{a}_{21}$ =**2**	u_2= λ_2*a_{22}=1	u_3=λ_i*a_{ij} =1

  We must note that the value of u_j does not consider the interplay between the Industry 5.0 solutions and their effect on each other indicated in the matrix B.

- Finally, the features of other organizations are compared based on suggested indicators of the GRI standards [120] and extended by experts in the field. It should be noted that these indicators are subject to further refinement and expansion as the field continues to evolve and develop. In this way, organizations can be positioned based on their sustainability performance and identify specific development strategies.

- The proposed QFD can be visualized as a network, enabling structural analysis through the interconnections of SDGs, GRI, and I5.0 developments. By representing these interlinkages as bipartite graphs [125], the indirect relationships and interactions can be more effectively illustrated. A bipartite graph is a type of graph in which the set of vertices (or nodes) can be divided into two distinct, non-overlapping groups such that no two vertices within the same group are connected by an edge. Instead, all edges connect vertices from one group to the other. The network is then denoted as $G = (V, E)$, where G is the network, V represents the vertices. V vertex set can be

partitioned into non-empty subsets X, Y and Z, $X \cup Y = V$ and $X \cap Y = \emptyset$ and $Y \cup Z = V$ and $Y \cap Z = \emptyset$. Edges are indicated with E, and each edge of G has one endpoint either in X and one endpoint in Y, or one endpoint in Y and one in Z. The partition $V = X \cup Y$ or $V = Y \cup Z$ are the bipartitions of G. In this case, the subsets will be X, the SDG indicators, Y, the GRI indicators and we can denote Z as the Industry 5.0 solutions. By structuring it this way, indirect relationships across all subsets become more apparent, enabling a deeper understanding of interdependencies.

- Communities in networks can be detected, where the connection between the nodes is more dense indicating close interdependence. The Louvain method [126] is used for community detection to extract non-overlapping communities within each bipartite network.

  - SDG Targets - GRI Topic Standards network:
    Communities reveal alignment between sustainability goals and targets and organizational reporting initiatives, supporting the identification of where organizational efforts support the SDGs and where gaps exist.
  - GRI Topic Standards - Industry 5.0 solutions network:
    Communities highlight synergies between organizational sustainability reporting and development solutions, guiding strategic collaboration and increasing impact.

  Understanding these communities can lead to more targeted, strategic actions in sustainability reporting and implementation, benefiting both organizations and broader global development efforts.

The systematic analysis of the interplay between SDGs, GRI Topics/sustainability requirements and the potential Industry 5.0 solutions provides a deeper understanding of the synergies between these elements. However, given the numerous potential relationships between SDGs, requirements, and solutions, a QFD-based analysis may become complex due to its extensive nature. Consequently, a network-based representation and evaluation can offer supplementary insights and reveal bridges between sustainability goals, requirements and Industry 5.0 solutions. By doing so, organizations can better prioritize their development efforts, improve their competitive positioning, and increase transparency, all of which contribute to long-term value creation. Although, it is important to emphasize that

this method cannot be fully understood in isolation; rather, it requires experts within the organization to utilize the acquired information to formulate a tailored strategic plan for the organization.

4.4 Results and discussion

In this section it is aimed to provide a comprehensive overview, which includes general observations and highlights the customizable nature of the proposed method. Furthermore, the example model is not tailored to any single organization; however, its behavior and outcomes are briefly examined in the context of specific organizations in certain cases.

The proposed interactions have been identified for 17 SDGs and 61 SDG targets, 141 GRI Topics, 18 Industry 5.0 solutions. To demonstrate the applicability of the method, an exploartive study for identifying key relationships between sustainability requirements and potential Industry 5.0 developments if formed, which is a selected submodel of the whole identified model by including only seven GRI Topics in the study, namely the General Disclosure, Economic Performance, Indirect Economic Impact, Market Presence, Producement Practices, Anti-competitive Behavior, Materials, Energy, Waste, and Employment. The Industry 5.0 solutions were identified based on the work of Ghobakhloo *et. al* [103], who identified 16 sustainable development functions of Industry 5.0. Those proposed solutions cover areas of Operational and resource efficiency (ORE), Open sustainable innovation (OSI), Renewable integration (RIN), Real-time communication (RTC), Supply chain adaptability (SCA), Supply chain modularity (SCM), System integration and interoperability (SII), Service-orientation and personalization (SOP), Sustainable thinking (STH) Business process monitoring (BPM), Upskilling and reskilling (UPR), Value network integration (VUI), Data sharing and transparency (DST), Intelligent automation (INA), Employee technical assistance (ETA), Circular intelligent products (CIP). However, we must note, that Industry 5.0 transformation requires a balanced "technological advancement with human-centric values, emphasizing the importance of resilience, sustainability, and the well-being of workers" [7]. In this way, to give an additional focus on the human-in-the-loop aspect, this work have been extended with the Operator 4.0 and Human-centric management. Even though the Operator 4.0 concept is rooted in Industry 4.0, it

remains highly relevant in the Industry 5.0 context due to its focus on empowering workers through advanced technological support. The Operator 4.0 concept reflects to the functional, technological developments on the shop floor and integrates the aspects of how emerging technologies can assist the work and well-being of operators. This aligns directly with the specific technological inputs detailed in Industry 5.0 Community of Practice (CoP 5.0), such as Computation, AI/ML, Robotics, Wearables, etc. [7] and the technical interaction skills required [7]. Furthermore, technologies can be categorized based on the which skills of the operation we want to empower, e.g. analytical skills, augmented support, collaboration and social interactions, health and well-being. Technologies such as smart glasses, personal displays, smart watches, tablets, smart gloves and clothes, ergonomic and adjustable work environment, or e.g. motion detection provide solutions to ease operators physical and mental workload as well as provides data-driven feedback on performance [124]. Complementing this technological focus, Human-centric management adresses the higher level managerial and strategic aspects of creating sufficient workplace culture that prioritizes inclusivity, collaboration, and continuous learning. This aligns with CoP 5.0 human centricity in terms of including the necessary workforce competencies and mindsets, such as strong entreprenurial mindset, inter-cultural, inter-disciplinar and diversity-oriented mindset, etc., the establishment of a common vision and inclusive culture, and the crucial organizational processes that foster learning, well-being, participation, and ethical technology deployment [7]. It serves as a foundation of prioritizing workers' both physical and mental well-being, empower their skills. This approach also includes leadership development [127], ethical decision making and transparent data management [128] practices. By integrating these principles, organizations can create a sustainable and resilient workforce, where technological advancements complement human capabilities rather than replace them, ultimately driving innovation and long-term success. We must note that each solution can be further broken down into technical developments that contributes to perform on the given Industry 5.0 solution. Within the Industry 5.0 framework, technological solutions of Operator 4.0 and organizational human-centric management strategies must intertwine and complement each other to create human-centered, resilient, and sustainable work environments.

The submodel was selected based on expert experience in Hungarian manufacturing organizational collaborations. The QFD-based representation of organizational sustainability development for the study is shown in Figure 4.3. Each part of the

QFD-based model is presented, and the connections between the elements are discussed in the indicated subsections.

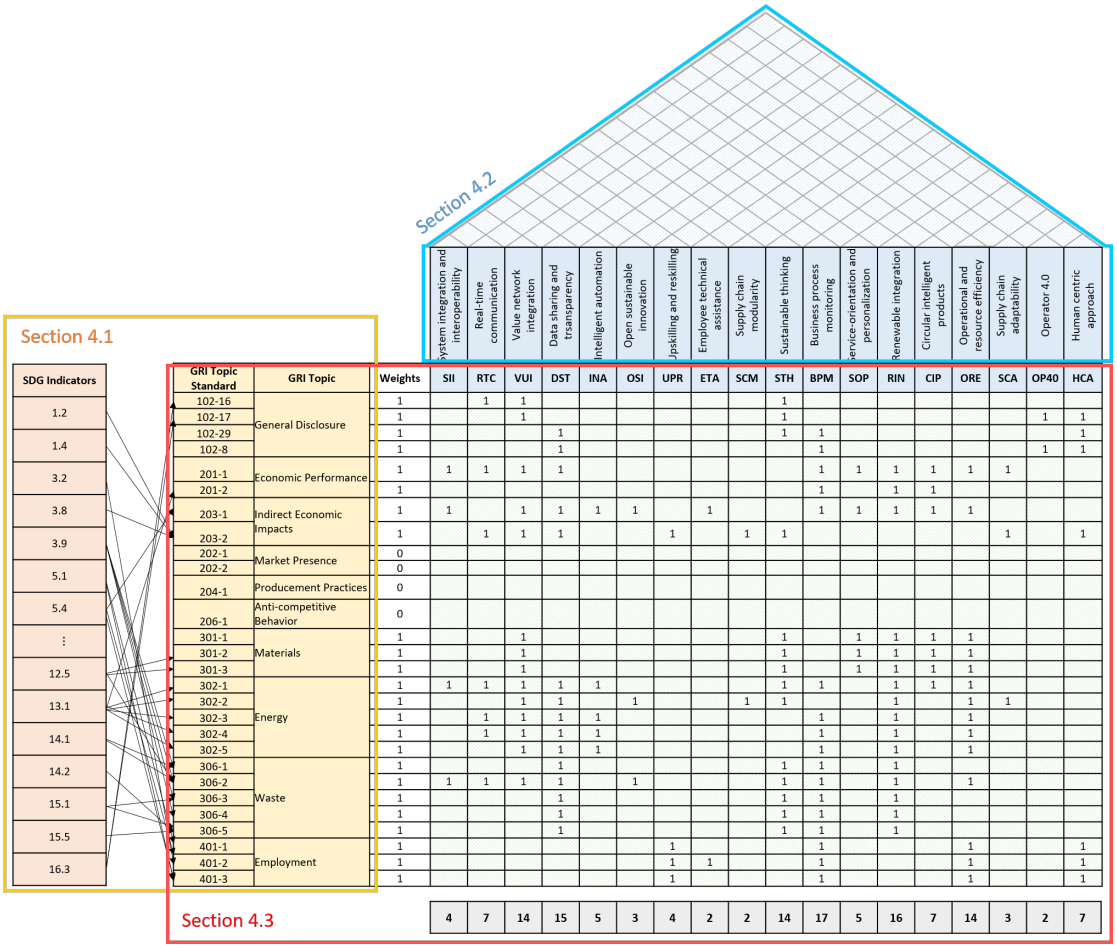


FIGURE 4.3: Framework of QFD-based sustainability-focused key Industry 5.0 solution exploration. (Source: Ref. [4])

4.4.1 Connecting SDG targets to sustainability requirements

The study includes ten GRI Topics, from which the following seven are selected by being weighted with one: General Disclosure, Economic Performance, Indirect Economic Impacts, Materials, Energy, Waste and Employment. Note, that the weights (λ) assigned to the topics in the model are not restricted to binary values of 1 and 0. Rather, the weights can be tailored to the specific needs of the organization, allowing for greater flexibility in capturing the relative importance of each topic. Accordingly, a topic deemed to be of greater significance within the organization may be assigned a higher weight to reflect its relative importance.

The selected sustainability requirements are linked to SDG targets based on the work of the United Nations and the Global Reporting Initiatives [120] as shown in the related reference work [4] in Appendix A. Furthermore, the indicators of measuring individual organizational performance on the selected requirements are indicated in the related reference work [4] in Appendix B.

In Figure 4.4, the summary distribution of the number of GRI Topics and GRI Indicators by SDGs are shown for a) the whole model, and b) the smaller-scale study with the selected requirements.

According to the selected requirements, SDG 8 (Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all) and SDG 12 (Ensure sustainable consumption and production patterns) have connections with the most selected GRI Topics thereby they are the most connected SDGs. However, concerning the full scale of GRI Topics (not limited to the application study), the most connected SDGs are SDG 8, SDG 16 (Peace, justice and strong institutions), SDG 3 (Good health and well-being), SDG 6 (Clean water and sanitation), and SDG 12.

The high connectivity of SDG 8 and SDG 12 can be explained by both substantive and methodological factors. Substantively, the two goals represent closely interrelated dimensions of industrial value creation: SDG 8 addresses economic productivity, technological upgrading, employment, and decent work, whereas SDG 12 focuses on the material, energy, waste, and consumption consequences of production. Their overlap is particularly explicit between Targets 8.4 and 12.2, which both address resource efficiency and the decoupling of economic growth from environmental degradation and are monitored through common material-footprint and domestic-material-consumption indicators [129]. Recent research on circular-economy strategies also found that their strongest potential contributions are associated with SDGs 8, 12, and 13, particularly through regenerative production, product-life extension, cleaner energy use, and human-inclusive industrial practices [130]. At the organizational level, empirical evidence from European SMEs further indicates a significant association between resource-efficiency practices, green employment, and environmental skills, providing an additional link between the employment-related dimension of SDG 8 and the responsible-production dimension of SDG 12 [131]. This interpretation is also consistent with the Industry 5.0 perspective, which connects industrial prosperity and technological development

with respect for planetary boundaries and the well-being of industrial workers [132].

From a methodological perspective, the observed connectivity is also influenced by the composition of the examined submodel, which includes GRI Topics related to economic performance, employment, materials, energy, and waste. Consequently, the result reflects a theoretically and empirically supported relationship, but it should not be interpreted as evidence that SDG 8 and SDG 12 are universally the most important or most interconnected goals. Rather, their high degree indicates the breadth of the organizational and reporting-related impact areas shared by these goals within the selected model.

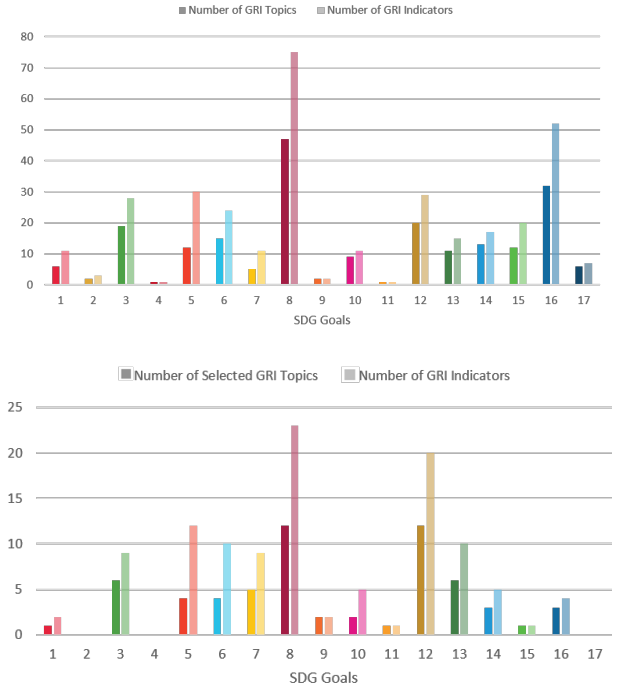


FIGURE 4.4: Number of GRI Topics and GRI Indicators by SDGs for a) the whole model; b) the submodel utilized for the study. (Source: Ref. [4])

The assessment of economic growth (SDG 8.1) can be conducted by examining the economic performance of organizations. This can be achieved by measuring the direct economic value generated by the organization, which is typically represented by organizational revenues. Additionally, economic value distribution must also be taken into account. This includes various components such as operating costs, employee wages, and benefits, payments to providers of capital, payments to the government by country, and community investments (GRI 201-1) [133].

Development-oriented policies on supporting creative, innovative productive activities, job and enterprise creation (SDG 8.3) and equity for all (SDG 8.5) have the potential to foster local economic development by establishing flexible markets that can readily accommodate fluctuating consumer demands while effectively reflecting the costs of goods [134] and the indirect economic impacts (GRI 203-2) [135].

To promote sustainability and economic productivity, it is important to approach the creation of organizational value from a sustainability perspective [136]. This includes forming strategies including diversification, technological upgrading, and innovation (SDG 8.2). Digital advancements such as real-time communication, data sharing, and monitoring can be utilized to optimize organizational processes across the value network, leading to improvements in energy consumption, production efficiency, and environmental performance of products throughout their life cycle. Moreover, there is a growing demand for smart products and circular smart manufacturing [137], as well as a system-based approach for organizational circular economy [138].

Circular economy models are also gaining increasing attention due to their potential to mitigate climate-related risks (GRI 201-2) [133], reduce waste generation (GRI 301-1, 301-2, 301-3) [139] and related impacts (GRI 306-1, 306-2, 306-3, 306-4) [140], decrease energy consumption within and outside of the organization (GRI 302-1, 302-2) [141], reduce the energy requirements of products and services (GRI 302-4, 302-5) , and promote efficiency in sustainability management, consumption, and production while decreasing the material footprint (SDG 8.4, SDG 12.2) [142].

Responsible consumption and production are fundamental pillars of sustainable development as they directly affect the environment. The production processes and consumption patterns have environmental impacts, and hence there is a need to make these processes more responsible. The ultimate goal is to reduce the environmental impacts of production and consumption activities while ensuring equitable access to adequate resources for all [143]. Therefore, to promote smarter product use and manufacturing, extend the lifespan of products and their parts, and useful application of materials, the following strategies should be considered during strategy-making, such as recover, recycling, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink, and refuse [144]. It includes reducing waste generation through prevention, reduction, recycling, and reuse (SDG 12.5) (GRI

301-1, 301-2, 301-3), and minimizing their adverse impacts on human health and the environment (SDG 12.4) (GRI 306-1, 306-2, 306-3, 306-4).

The consideration which SDGs and sustainability requirements (GRI Topic Standards) should be measured within an organization can be also industry specific. For example for automotive industry it has been revealed that the most commonly reported SDG goals (based on seven manufacturers) are the SDG6 - Clean water and sanitation, SDG8 -Decent work and economic growth, SDGG9 - Industry, innovation and infrastructure, SDGG10 - Reduced inequalities, SDG 11 - Sustainable cities and communities and SDG12 - Responsible production and consumption [145]. Also the focus points may differ not just industry, but country and institutional factors such as politics an low, economics and finance, society and culture, technology and innovation, education and labor, and sustainability [146].

We must note that the transition towards a sustainable and human-centered economy relies on customer, business, and government parties' perceptions and efforts. A change in consumption patterns is not solely enough, but the environmental impacts of production must be reduced, and regulated through governmental policies and initiatives in investing in digital technologies supporting sustainable development aspirations [143]. Digital and disruption technologies can contribute to the realization of SDGs and bring a broad range of implications for organizations, customers and the workforce [147]. The emergence of technologies such as AI-, data-, model-driven developments, robotics, IoT, etc. poses a challenge to both leaders and innovators, requiring them to reevaluate their organizational and business strategies for the future [147].

4.4.2 Causation matrix of Industry 5.0 solutions

The causation matrix of Industry 5.0 solutions identifies their relationship. We assume a one-way causal effect in which information is based on the work of Ghobakhloo *et al.* [103] and have been extended by the authors with the Operator 4.0 [124] and Human-centric management.

The causation matrix indicates, how would a change in ID_i affect ID_j. This information is stored in a B matrix as shown in Table 4.1, which is the causation matrix of the application study. Specifically, if $b_{j,k} = 1, j, k = 1, ..18$, solution ID_j has a direct causal impact on solution ID_k, as evidenced by the example

of Circular intelligent product (CIP) directly affecting Operational and resource efficiency (ORE), while the reverse is not true. If $b_{j,k} = 1^*$, solution ID_j has an indirect causal influence on ID_k through other Industry 5.0 solutions. For instance, Data sharing, and transparency (DST) have a direct effect on CIP, which in turn directly impacts ORE, thereby establishing an indirect causal connection between DST and ORE.

TABLE 4.1: Causation matrix of Industry 5.0 solutions. (Source: Ref. [4])

		BPM	CIP	DST	ETA	INA	ORE	OSI	RIN	RTC	SCA	SCM	SII	SOP	STH	UPR	VUI	OP40	HCA	Driving force
Business process monitoring	**BPM**	1	1	0	0	0	1	0	1*	0	1	0	0	1*	0	0	0	0	0	**6**
Circular intelligent products	**CIP**	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	**4**
Data sharing and trsansparency	**DST**	1	1	1	1	1*	1*	1	1	1*	1	0	0	1*	1	1	1	0	0	**14**
Employee technical assistance	**ETA**	1	1*	1*	1	0	1	1*	1*	1*	1*	0	0	1*	1	1*	0	1	0	**13**
Intelligent automation	**INA**	1	1*	1	1	1	1	1*	1	0	1	1	0	1*	1*	1	1*	1	0	**15**
Operational and resource efficiency	**ORE**	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	**2**
Open sustainable innovation	**OSI**	1*	1	0	1	0	1*	1	1	0	1	0	0	1	1*	1	0	0	0	**10**
Renewable integration	**RIN**	0	1	0	0	0	1*	0	1	0	1*	0	0	1*	0	0	0	0	0	**5**
Real-time communication	**RTC**	1	1	1	1	1	1*	1*	1	1	1	1*	0	1	1*	1*	1*	0	0	**15**
Supply chain adaptability	**SCA**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**
Supply chain modularity	**SCM**	1	1*	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0	0	**6**
System integration and interoperability	**SII**	1	1*	1	1	1	1*	1*	1	1	1	1	1	1	1*	1*	1	1	0	**17**
Service-orientation and personalization	**SOP**	1*	1	1*	0	0	1	0	1*	1*	1	0	0	1	0	0	0	1	0	**9**
Sustainable thinking	**STH**	1*	1	1*	1*	1*	1*	1	1	1*	1*	0	1*	1	1	1	1*	1	1	**17**
Upskilling and reskilling	**UPR**	1*	0	1*	1	0	1*	0	0	1*	0	0	0	0	1*	1	0	1	0	**8**
Value network integration	**VUI**	1	1	1	1*	1	1	1	1	1	1*	1*	0	1	1*	1*	1	1	0	**16**
Operator 4.0	**OP40**	1	1*	1	1*	1*	1	1*	1*	1	0	0	1*	1*	1*	1*	1*	1	0	**15**
Human-centric approach	**HCA**	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	**16**
Dependence force		**14**	**15**	**11**	**11**	**8**	**17**	**10**	**14**	**10**	**15**	**5**	**4**	**14**	**11**	**11**	**8**	**9**	**2**	

Industry 5.0 solutions considered in the analysis and their short description and importance regarding Industry 5.0 initiatives are as follows based on the work of Ghobakhloo *et al.* [103]. System integration and interoperability (SII) involves combining micro-modules of digital ecosystems within and across smart components of Industry 5.0, and enabling seamless communication between them [148]. Specific solutions include digital twins, LiDAR for precision mapping, and IoT platforms for interconnected operations. SII has important implications for sustainable development, as it provides stakeholders with open, democratized, access to value, and facilitates Real-time communication (RTC) and Value network integration (VUI). Value network integration involves horizontal and vertical integration of business processes throughout the whole supply chain, which in the case of Industry 5.0 can refer to the ISA-95 standard-based organizational structure (vertical) [149], and Industrial Data Spaces allowing horizontal communication and cooperation between supply chain members for reaching a common goal [150]. Key

enablers include blockchain for secure data exchange, AI-powered predictive analytics, and cloud-based ERP systems for supply chain synchronization. Thereby, VUI facilitates the integration of optimization algorithms, product customization, manufacturing agility, and collaboration [151], which are outcomes essential to the sustainability pillars of Industry 5.0. In this context, Real-time communication plays a vital role as provides seamless communication and data exchange between smart components in the value network to improve production reliability, work environment safety, risk management, and decision processes [152]. Technologies like 5G networks, edge computing for latency reduction, and machine-to-machine communication protocols are essential for RTC. RTC is also a critical component of establishing Data sharing and transparency (DST), which refers to the practice of making data available, and accessible to relevant stakeholders in a transparent and secure manner [153]. Specific tools include standardized ontologies, secure data lakes, and privacy-preserving analytics techniques. It requires a strong base of integrated standardized data models to ensure transparency and interoperability [154]. By doing so, it allows better decision-making, and cross-collaboration for a common goal such as reducing environmental impact or monitoring environmental performance across the value network [155]. DST and VUI enable to perform Open sustainable innovation (OSI) through close collaboration among the value network. OSI can support the operation of developing new products, services, and business models that contribute to sustainable development [156], and digital green innovation [157].

However, the developed systems, products and services must be continuously monitored and developed to remain competitive and efficient. To do so, Business process monitoring (BPM) through advanced technologies, real-time communication, data-driven analysis, and machine learning methods enables to track, analyze, and optimize business processes across the value chain and monitor key performance indicators, and supports data-driven decision-making, and early risk identification to improve overall business efficiency and effectiveness [6]. Examples include process mining tools, KPI dashboards, and anomaly detection systems powered by AI. The adaptation of BPM requires an integrated data and information sharing environment and advanced technologies. The integration of Intelligent automation (INA) involves the implementation of such technologies as artificial intelligence, machine learning, and robotics enable to create an automated, adaptive and sustainable production environment [158]. Specific solutions include collaborative robots (cobots), autonomous mobile robots (AMRs), and automated quality

inspection systems. In the context of Industry 5.0, it aims to achieve greater efficiency, flexibility, and resilience in manufacturing processes, leading to improved process, worker and resource productivity and reduced social and environmental impact [158]. INA is also identified as a direct enabler for Employee technical assistance (ETA) and Upskilling and reskilling (UPR).

ETA refers to the use of intelligent systems and digital technologies to provide technical support and assistance to workers and ensures that they are adequately trained to work with complex (cognitive/collaborative) systems [159]. Tools include augmented reality (AR) interfaces, dynamic work instructions, wearables, smart glasses and watches, personal displays, and virtual training simulators. Therefore, regarding UPR, the continuous development of skills and knowledge of the workforce is a must to meet the evolving needs of Industry 5.0 [160]. The Industry 5.0 concept emphasis the human-centric management (HCA) that prioritize empowering workers and create collaborative system where utilize technologies to enhance their efficiency, safety and well-being [8]. A manufacturing worker in such environment called Operator 4.0, who is equipped with digital skills and utilize e.g. augmented reality, wearables, and collaborative robots [22]. Examples include AR-enhanced (e.g. maintenance) tools and robotic exoskeletons to assist in physically demanding tasks, as well as performance monitoring, movement analysis, support of 5S workplace organization and digital twins. The HCA also triggers Sustainable thinking (STH), which refers to the integration of sustainability principles through the value network and takes into account social, economic, and environmental factors. Incorporating these principles, the Renewable integration (RIN) concept utilizing smart and renewable sources and materials for product design, as well as integrating renewable principles into the entire organizational culture are crucial features [161]. Solutions include energy harvesting technologies, biodegradable materials, and life cycle assessment tools. In this regard, Circular intelligent products (CIP) involve using Industry 5.0 technologies to design products that can function within the circular economy framework. Technologies like reverse logistics platforms, additive manufacturing for remanufacturing, and AI-based material recovery systems are pivotal. CIP ensures that products are designed and developed to be environmentally friendly across their life cycles [162]. The overall organizational objective utilizing Industry 5.0 technologies, tools and methods under sustainability principles, following circular integration, is to optimize processes and improve Operational and resource efficiency (ORE) to gain financial, and economic benefits [8] and improve green total factor productivity

[163]. Furthermore, mass customization initiatives are gaining increasing potential, and organizational Service-orientation and personalization (SOP) abilities are necessary to remain competitive [164].

Finally, Supply chain modularity (SCM) refers to the use of flexible and scalable supply chain components that can be easily reconfigured or replaced to accommodate changes in demand or production [165]. SCM allows for decentralization, and promotes Supply chain adaptability (SCA) to respond to market demands [165]. Specific enablers include modular automation platforms, digital twins for supply chain design, and adaptive manufacturing systems. The implementation of digital technologies has a positive impact on establishing sustainable supply chain practices [166]. Furthermore, supply chain modulatity contributes to sustainability aspects by supporting tracability, responsible sourcing, circular material flows, waste reduction and resilient collaboration across the supply chain. These aspects are particularly relevant for organizational sustainability performance, since environmental and social impacts increasingly emerge not only within firm boundaries, but across the broader value network.

The aforementioned Industry 5.0 solutions can be categorized based on their role in organizational transformation, with particular emphasis on their driving and dependency power. Table 4.1 also reveals the driving and dependency power of Industry 5.0 solutions, which can be categorized based on these two factors. These categories are shown in Figure 4.5. This categorization highlights which solutions are pivotal in establishing and stabilizing Industry 5.0 strategies, thereby becoming essential for overall organizational growth and innovation. It also identifies solutions that serve as primary initiators, capable of launching new processes and enhancing existing ones, thus acting as stable drivers of transformation while remaining less susceptible to external fluctuations. Additionally, the categorization reveals solutions that, while not serving as primary catalysts for change, are crucial for supporting and augmenting the capabilities of the more influential solutions. Finally, some solutions are identified as more isolated and specialized, playing a minimal role in shaping the broader strategic direction of Industry 5.0.

The blue cluster includes STH, RTC, DST, ETA, OSI and SOP exhibit strong driving and dependency power, signifying their importance in establishing stable Industry 5.0 strategies and driving transformation. For example, RTC can provide real-time monitoring of organizational processes (BPM), more efficient and automatic data gathering and analysis (INA), monitoring of product life cycle (CIP),

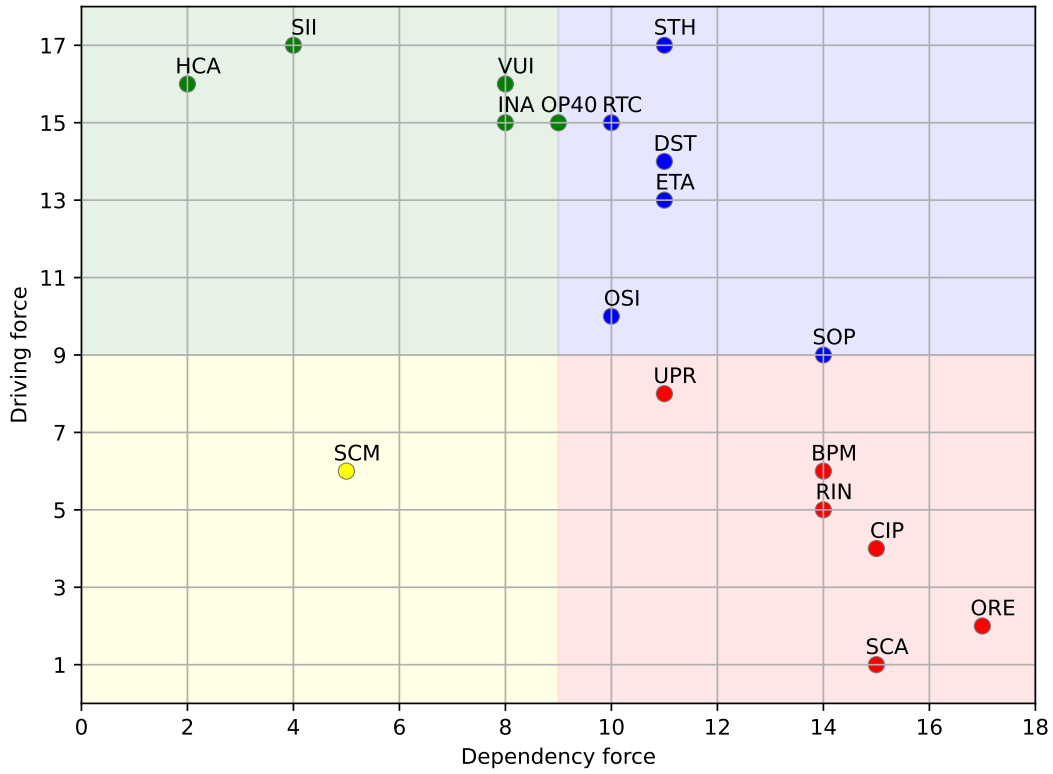


FIGURE 4.5: Classification of Industry 5.0 solutions based on their dependency and driving force (Source: Ref. [4])

etc. [103]. The green cluster includes solutions with strong driving and relatively low dependency force, such as HCA, OP40, VUI, SII, and INA, which play a critical intermediary role in transferring both driving and dependency values but are unstable, meaning that any action taken on them can impact other functions and result in a reflexive effect on themselves. The red cluster includes BPM, CIP, ORE, RIN, SCA, SOP, and UPR exhibit weak driving but strong dependency power, meaning that their development relies on various aspects and may require a certain level of maturity to adapt. Finally, the yellow cluster includes SCM, which has weak driving and dependency force.

We must note that the implementation of Industry 5.0 solutions may entail substantial financial investment and necessitate a shift in organizational culture, thereby posing significant challenges [167]. To effectively address these challenges, it is essential to prioritize these areas of concern through a coordinated effort. Given the resource-intensive and structurally complex nature of such initiatives, a targeted and strategic approach is essential to effectively manage changes and

ensure the achievement of sustainable progress toward desired outcomes.

4.4.3 Relationship matrix of sustainability requirements and Industry 5.0 solutions

The relationship matrix of the application study is shown in Table 4.2. It identifies the connection between sustainability requirements and Industry 5.0 solutions. This information is stored in an A matrix, where if $a_{i,j} = 1, i = 1, ..., 24, j = 1, ..18$, the i-th requirement can be improved and influenced by the j-th solution. The relationships are identified by experts in the field.

TABLE 4.2: Relationship matrix of sustainability requirements and Industry 5.0 solutions (Source: Ref. [4])

GRI Topic Standard	GRI Topic	Weights	SII	RTC	VUI	DST	INA	OSI	UPR	ETA	SCM	STH	BPM	SOP	RIN	CIP	ORE	SCA	OP40	HCA
102-16	General Disclosure	1		1	1							1								
102-17		1			1							1							1	1
102-29		1				1						1	1							1
102-8		1				1							1						1	1
201-1	Economic Performance	1	1	1	1	1							1	1	1	1	1	1		
201-2		1											1		1	1				
203-1	Indirect Economic Impacts	1	1		1	1	1	1		1			1	1	1	1	1			
203-2		1		1	1	1			1		1	1						1		1
301-1	Materials	1			1							1		1	1	1	1			
301-2		1			1							1		1	1	1	1			
301-3		1			1							1		1	1	1	1			
302-1	Energy	1	1	1	1	1	1					1	1		1	1	1			
302-2		1			1	1		1			1	1			1		1	1		
302-3		1		1	1	1	1						1		1		1			
302-4		1		1	1	1	1						1		1		1			
302-5		1			1	1	1						1		1		1			
306-1	Waste	1				1						1	1		1					
306-2		1	1	1	1	1		1				1	1		1		1			
306-3		1				1						1	1		1					
306-4		1				1						1	1		1					
306-5		1				1						1	1		1					
401-1	Employment	1							1				1				1			1
401-2		1							1	1			1				1			1
401-3		1							1				1				1			1
			4	7	14	15	5	3	4	2	2	14	17	5	16	7	14	3	2	7

The relationship matrix allows us to define which GRI Topic is influenced by which Industry 5.0 solution and also gives us a perspective on how complex the composition of GRI Topics. The last row in Table 4.2 indicates the importance rank of the Industry 5.0 solutions. The ones with the highest value are the most important solutions to invest in and have a potentially great effect on the selected sustainability requirement. However, the resulting ranking should not be interpreted as universally valid for all organizations or sectors. The importance of Industry 5.0 solutions depends on the selected sustainability requirements, the applied GRI topics, the sectoral context, regulatory environment, organizational maturity, available resources and strategic priorities of the company. Therefore, the matrix provides a general decision-support structure that can be adapted to specific organizational contexts. In practical applications, the relationships and

weights should be reviewed and, if necessary, adjusted with company- or sector-specific expert input. We must note that the interplay between the Industry 5.0 solutions and their effect on each other is not included in the calculation.

The importance ranking of the Industry 5.0 solutions is shown in Figure 4.6, which provides an insight into their composition.

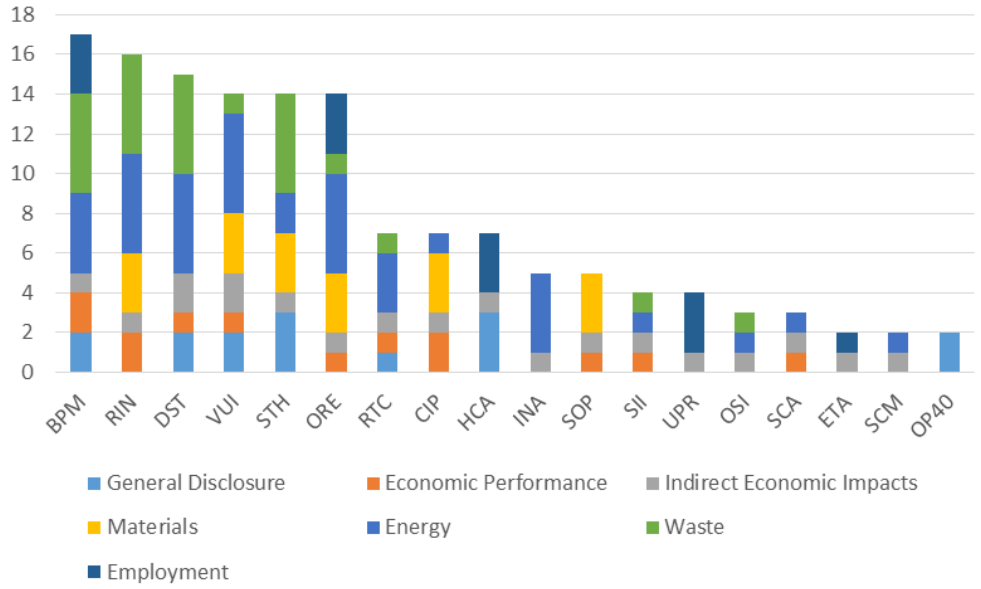


FIGURE 4.6: Importance ranking of Industry 5.0 solutions and their composition (Source: Ref. [4])

In the application study, the most influential Industry 5.0 solution for sustainability requirements is Business process monitoring (BPM), Renewable integration (RIN), and Data sharing, and transparency (DST). However, concerning all the GRI Topics not just the smaller-scale study, Sustainable thinking (STH) had the most significant influence, followed by DST, BPM, the human-centric management (HCA), then Operational and resource efficiency (ORE), and RIN. Figure 4.6 also indicates the composition of the importance rank, including how much and which GRI Topics are influenced by the given Industry 5.0 solution. For example, BPM is the most influential solution, and influences the most GRI Topics/sustainability requirements. The more complex the composition of the Industry 5.0 solution, the more area it can be utilized and might be more general. On the contrary, for example, OP40 is the least influential and only includes the Employment requirements, but it is highly focused and specific.

Regarding a recent study, it has been revealed that 85% of environmental, 65% economic, and 50% societal GRI standards are influenced by Industry 5.0 developments, such as advanced robotics, additive manufacturing, augmented reality, simulation, IoT, big data analytics (related to INA, RTC, ORE), horizontal and vertical integration (related to SII, VUI, SCA), cyber security (related to DST) [168]. Considering the relationship matrix, more precisely, GRI Topic Standards influenced by the most Industry 5.0 solutions are 203-1 (Infrastructure investments and services supported), 201-1 (Direct economic value generated and distributed), and 302-1 (Energy consumption within the organization). For example, energy consumption within the organization is connected to SII, RTC, VUI, DST, INA, STH, BPM, RIN, CIP, and ORE. The monitoring, control, and optimization of energy consumption have a pivotal role in improving organizational energy efficiency and reducing environmental impact [169]. There is an increasing need to make buildings and productions cleaner and smarter, manage energy through IoT-based devices, as well as integrate equipment and systems for better operational and resource efficiency [169]. Energy distribution and management require data acquisition all over the network [170], which demands efficient automated data sharing and real-time communication to support energy management and the use of advanced energy consumption strategies and optimization methods [171]. Furthermore, smart and connected sensors can provide a real-time overview of the organizational environment, e.g. climate, temperature, energy consumption, etc. [172], which information can support energy management strategies to prevent losses and improve performance and optimize source-productivity [173].

For a better understanding of the importance of the elements and their structure, the connections of the SDGs-GRI Topics-Industry 5.0 solutions are visualized as bipartite networks in Figure 4.7. The edges represents the interaction points between SDGs and GRI Topics, so which topic supports the development of a certain SDG, and the linkages between GRI Topics and the Industry 5.0 solutions, so which development tool can be utilized for improving on a topic.

The network representation can be quite complex in the case of increasing the selected GRI topics. In such cases, a bipartite network projection offers a valuable analytical framework for examining the interlinkages between node sets, such as SDG Targets and GRI Topic Standards, as well as GRI Topic Standards and I5.0 solutions. The projection of a bipartite network onto one sets enables to represent the relationships among the nodes based on their common connections to nodes

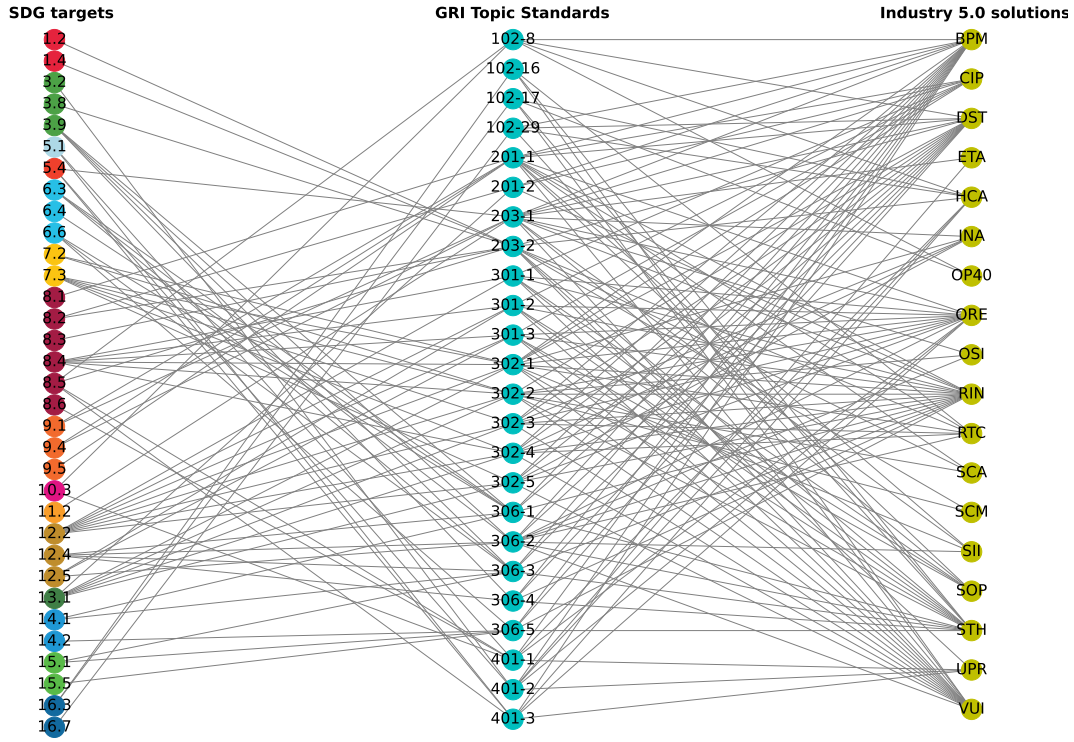


FIGURE 4.7: Bipartite network representation of the connections between SDG targets-GRI Topic Standards -Industry 5.0 solutions. (Source: Ref. [4])

in the other set. By analyzing the structure of the projected network, we can identify e.g. clusters of closely related topics. This approach facilitates a deeper understanding of the relationships within the dataset, making it possible to draw insights into the multidimensional nature of sustainability reporting practices and the interconnectedness of sustainability issues.

The bipartite representation of the SDG Targets and GRI Topic Standards network (right side of the network represented in Figures 4.7) is shown in Figure 4.8 and 4.4.3. In Figure 4.8 the bipartite network is projected onto the SDG Targets, while in Figure 4.4.3 onto the GRI Topics Standards. The node sizes represent the centrality of the node, and the thickness of the edges represents the weights, which are the number of linkages between two nodes, therefore the weight shows shows how many a) GRI Topic Standards, b) SDG Targets two nodes are connected through.

In Figure 4.8 SDG Targets are linked to each other if they are both linked to the same GRI Topic Standard. This means that the connected SDG Targets are

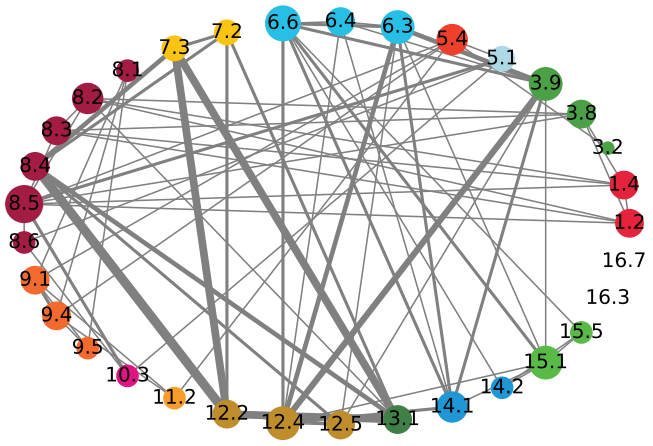


FIGURE 4.8: Projected network of the SDG Targets from the bipartite network of SDGs-GRI Topics positioned in circular layout for better readability. (Source: Ref. [4])

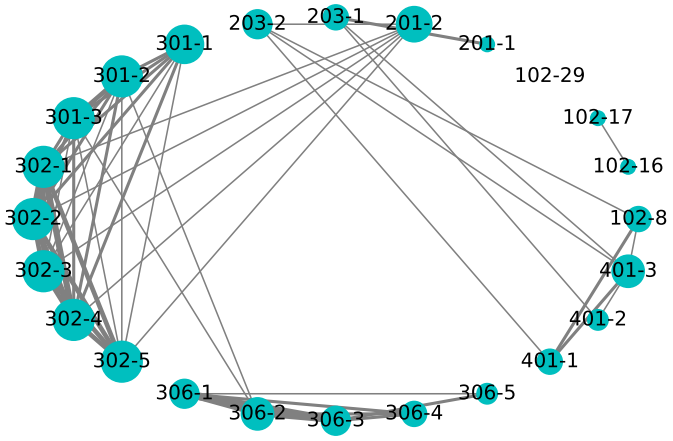


FIGURE 4.9: Projected network of the GRI Topic Standards from the bipartite network of SDGs-GRI Topics positioned in circular layout for better readability. (Source: Ref. [4])

related through a common reporting standard. In this subfigure, the most central element is SDG 8.5 - "Full employment and decent work with equal pay" with a value of 0.28, followed by SDG 6.6 - "Protect and restore water-related ecosystems" with a value of 0.25. Then, SDG 3.9, SDG 6.3, SDG 6.3, SDG 12.4 and SDG 15.1 has centrality 0.21875. Those nodes that are not linked together are connected to GRI Topic Standards that have no influence on other SDG Targets, e.g. SDG 16.7 - "Ensure responsive, inclusive, participatory and representative decision-making at all levels " is linked to GRI $102-29$ - "Identifying and managing economic, environmental, and social impacts", but this GRIs has no other related SDG Targets in the example.

In Figure 4.4.3 GRI Topic Standards are linked to each other if they are both

linked to the same SDG Target. This implies that the connected GRI Standards are relevant for reporting on the same SDG Target.

The bipartite representation of the GRI Topic Standards and Indutry 5.0 developments network (right side of the network represented in Figure 4.7) is shown in Figures 4.10 and 4.11. In Figure 4.10 the bipartite network is projected onto the GRI Topic Standards, while in Figure 4.11 onto the Industry 5.0 solutions. The node sizes represent the centrality of the node, and the thickness of the edges represents the weights, which are the number of linkages between two nodes, therefore the weight shows how many a) Industry 5.0 solutions, b) GRI Topic Standards two nodes are connected through. Both Figures are highly interlined showing the complexity of the network.

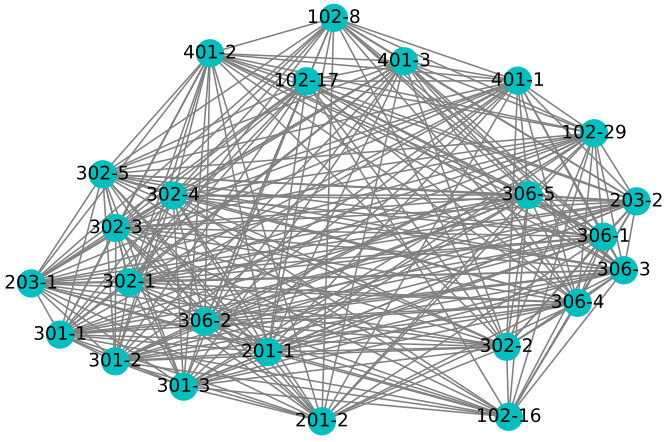


FIGURE 4.10: Projected network of the GRI Topic Standards from the bipartite network of GRI Topics-Industry 5.0 solutions. The node sizes represent the centrality of the node, and the thickness of the edges represents the weights, which are the number of linkages between two nodes. (Source: Ref. [4])

In Figure 4.10 GRI Topic Standards are linked to each other if they are both linked to the same Industry 5.0 solution. This means that the connected GRI Topic Standards are related through a common Industry 5.0 solution. The nodes are highly interlinked since the Industry 5.0 solutions contribute to various GRI sustainability requirements. One of the most central elements is energy (GRI 302) and waste (GRI 306)-related GRI Topic Standards. One of the most linked nodes are GRI 302-1 "Energy consumption within the organization" and GRI 306-2 "Management of significant waste-related impacts" through eight Industry 5.0 solutions.

In Figure 4.11 Industry 5.0 solutions are linked to each other if they are both linked to the same GRI Topic Standard. This means that the connected SDG Targets

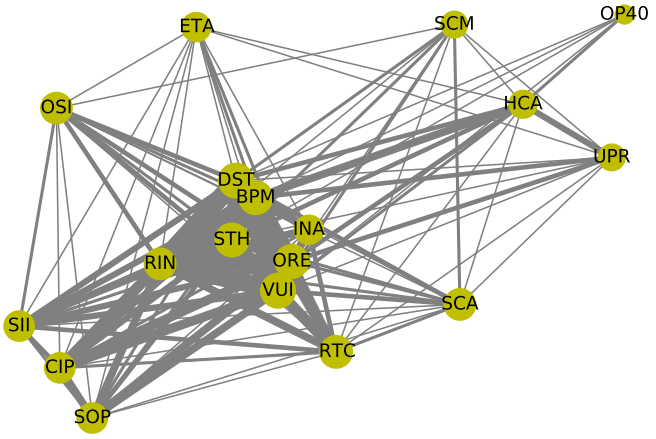


FIGURE 4.11:

FIGURE 4.12: Projected network of the Industry 5.0 solutions from the bipartite network of GRI Topics-Industry 5.0 solutions. The node sizes represent the centrality of the node, and the thickness of the edges represents the weights, which are the number of linkages between two nodes. (Source: Ref. [4])

are related through a common reporting standard. Value network integration (VUI), and Data sharing and transparency (DST) are the most central elements with value 1.0, followed by Business process monitoring (BPM), Operational and resource efficiency (ORE) and Sustainable thinking (STH) with the value of 0.9412. BPM and DST has the most linkages between them with the value of 13, meaning that they connect through 13 GRI Topics Standards. It is followed by DST and RIN with the value of 12, ORE and RIN, ORE and VUI, and RIN and VUI with the value of 11.

Communities within the two bipartite network is detected as shown in Figures 4.13 and 4.14. The communities in the SDG Targets and GRI Topic Standards network is in Figure 4.13, while the communities in the GRI Topic Stanrdards and Industry 5.0 solutions network is shown in Figure 4.14. The colored labels (A-G) represent distinct communities, with each color corresponding to a specific cluster of interconnected elements within the bipartite networks. It is important to note that while the same color scale is used in both subfigures, the colors do not imply that the same communities exist across both networks. Instead, the colors are used to identify different clusters within each network independently. The grayscale shading in the matrices further emphasizes areas of interaction within these networks.

The communities emphasize certain sustainability issue-related developments, such

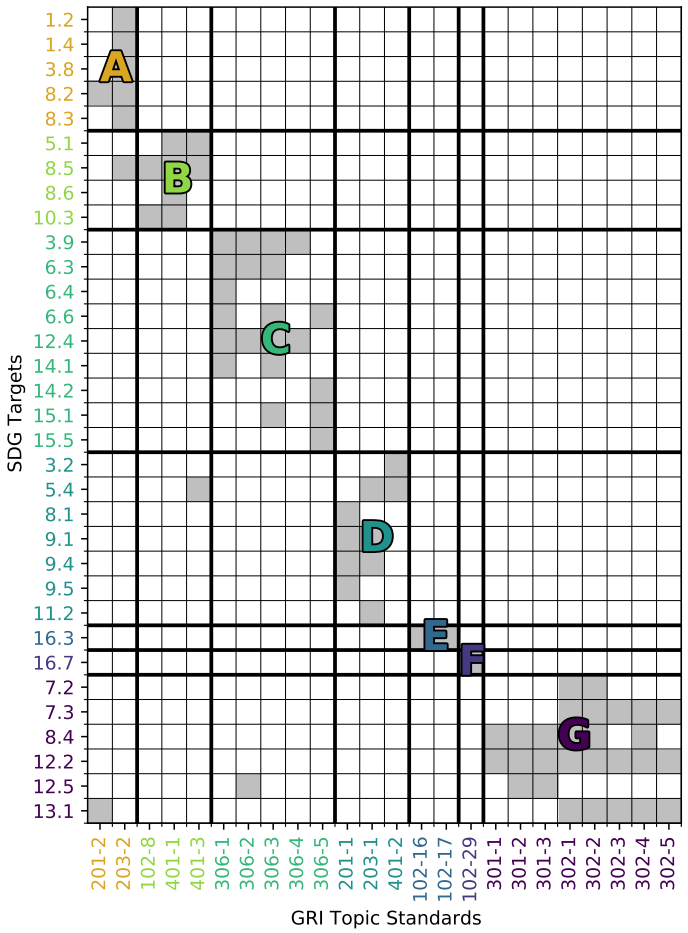


FIGURE 4.13: Communities in the bipartite networks of the SDG Targets and GRI Topic Standards. Items in the same communities are indicated with matching colors. (Source: Ref. [4])

as in Figure 4.13, the orange 'A' community emphasizes enhancing infrastructure, supporting vulnerable populations, and fostering innovation and productivity in the economy. The light green 'B' community highlights the importance of integrating sustainability and social responsibility into organizational reporting practices through reporting on workforce composition, employment patterns, and equality measures and ensuring gender equality, decent work, economic growth, and reduced inequalities. The green 'C' community emphasizes the importance of environmental sustainability, waste management, and the protection of ecosystems. The associated GRI standards (306 series) highlight a structured approach to reporting on waste management impacts, reinforcing the goals of reducing pollution and enhancing ecosystem resilience. These efforts are crucial for ensuring a healthy

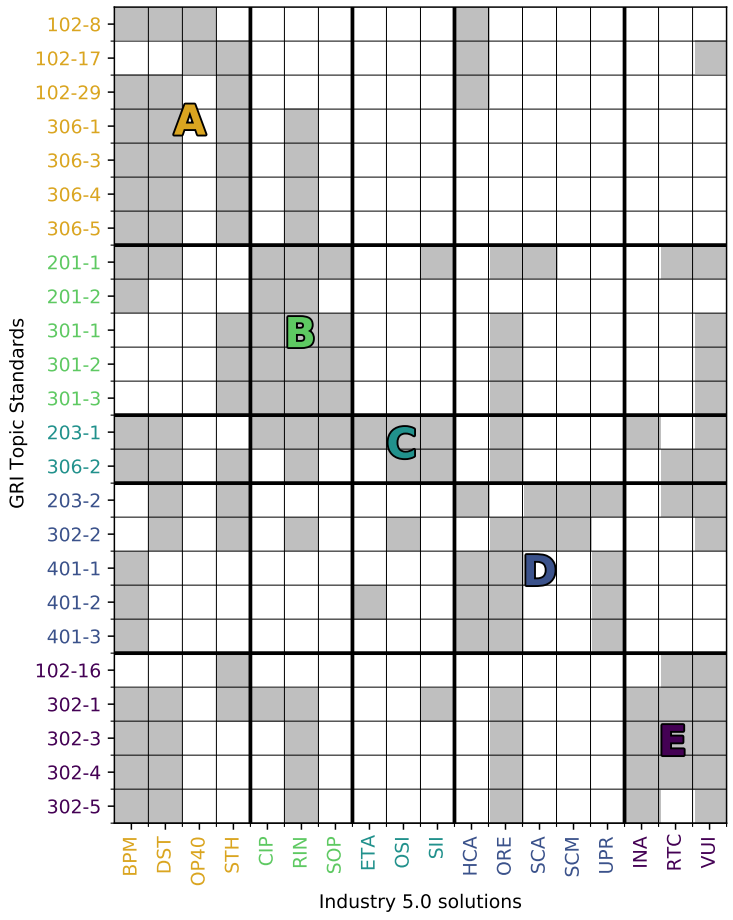


FIGURE 4.14: Communities in the bipartite networks of the GRI Topic Standards and I5.0 solutions. Items in the same communities are indicated with matching colors. (Source: Ref. [4])

environment and a sustainable future. The greenish blue 'D' community focuses on improving health outcomes, valuing unpaid care work, fostering economic growth, developing sustainable and resilient infrastructure, and enhancing scientific research and technological innovation. The associated GRI standards emphasize the economic impact and benefits of the initiatives, highlighting how sustainable practices in infrastructure and labor can support broader socio-economic goals. Furthermore, organizations can track their contributions to public health, gender equality, sustainable economic growth, and resilient infrastructure development through these measures. The blue 'E' community focuses on goals related to strong institutions, justice, and ethical business practices. These measures are essential for fostering a transparent, just, and accountable environment. The light

purple 'F' community fosters transparent, inclusive, and accountable decision-making structures, which are vital for sustainable development and the promotion of justice, equity, and participation at all levels of governance. The purple 'G' community emphasizes SDG targets that focus on enhancing renewable energy use, energy efficiency, sustainable resource management, waste reduction, and climate resilience. The associated GRI standards support these goals by providing metrics for tracking material use, energy consumption, and waste management practices. By aligning organizational practices with these SDG targets and GRI standards, companies can contribute to global sustainability efforts, promote economic growth that is decoupled from environmental degradation, and strengthen resilience against climate-related challenges.

The communities formed in Figure 4.14 highlight the approach of managing sustainability and operational efficiency, fostering ethical practices, and driving technological advancements. The orange 'A' community focuses on managing ethical, sustainable, and waste-related practices by ensuring efficient and transparent operation and long-term strategic focus on environmental and social impacts and risks. The light green 'B' community focuses on sustainability and innovation by emphasizing circular intelligent products and renewable energy integration. They prioritize service orientation and personalization to enhance user experience and satisfaction. The community strives to advance environmental responsibility while improving service quality through advanced, tailored solutions. The greenish blue 'C' community focuses on infrastructure development, waste management, and innovation and enhances sustainability through collaborative efforts and efficient use of resources. The blue 'D' community focuses on human-centric management, energy efficiency, and adaptable supply chain practices. It fosters that social well-being and organizational agility can be improved through operational and resource efficiency, enhancing supply chain flexibility, and upskilling the workforce. The purple 'E' community emphasizes ethical standards, energy management, and automation with a focus on reducing energy consumption and aligning operations with sustainable practices.

4.5 Conclusion

The evolution of Industry 5.0 has provided a distinct perspective that highlights the crucial importance of aligning digital transformation with socio-economic and

environmental priorities. "Research and innovation drive the transition to a sustainable, human-centric and resilient" [8] industrial operations. To achieve such, a shift in consumer behavior, production impact, and governmental policies are required [143] and the aligning of sustainability-related metrics and indicators is required to provide a frame for sustainable production processes [174].

To reduce environmental impact, promote worker well-being, and ensure resilient business operations, organizations must establish a culture and strategy that prioritizes sustainability and human-centric principles aligned with Industry 5.0 principles. The systematic development and reporting cycle of Industry 5.0 can assist organizations in assessing their transition progress also in Environmental, Social and Governance practices. However, the contribution of Industry 5.0 towards sustainable development values is currently under-investigated [103], and decision-support tools are needed to identify which Industry 5.0 solutions can support specific sustainability requirements.

To address this need, a decision support and development tool is proposed that is built upon the QFD standardized method.

While previous studies have explored the use of QFD within Industry 5.0, they primarily focus on specific domains such as sustainable supply chain design, often lacking integration with broader organizational performance indicators and reporting frameworks. The novelty of our approach lies in extending the traditional QFD methodology by incorporating standardized sustainability frameworks (GRI standards and SDG targets) and enhancing relational analysis through network science. This method enables a more holistic and systemic identification of how Industry 5.0 solutions align with specific sustainability requirements and organizational goals. Our approach not only identifies key enablers but also supports decision-making by revealing critical interdependencies, driving factors, and performance implications, thereby offering a practical and scalable tool for organizations aiming to align their development with Industry 5.0 and sustainability imperatives. The QFD-based method includes three parts: 1) identification of the connections between SDGs and sustainability requirements based on the GRI Topic Standards [120]; 2) a causation matrix of Industry 5.0 solutions (based on [103], which has been extended with Operator 4.0 and Human-centric approach that identify the driving and dependency factors of each solution and their synergies; 3) a relationship matrix of sustainability requirements and Industry 5.0 that

identifies which investments drive which sustainability requirement and organizational performance on SDG goals and targets.The relationship matrix has also been analyzed through network analysis identifying the direct and indirect relationships in the bipartite graphs of SDGs and GRI Topics, and the GRI Topics and Industry 5.0 solutions. Furthermore, identifying communities in the bipartite graphs allows to find closely interlinked sub-networks. The methodology only provides guidance to identify key relationships and potential solutions and tools to develop organizational performance and sustainability and reporting. The methodology cannot be utilized by itself as a strategic plan, it requires organizational experts and additional considerations for tailored strategy development.

Furthermore, we must note that since in Hungary Industry 5.0 and GRI-based reporting are not yet widely adopted, therefore a complete application study cannot be represented, but an experience-based example. Based on the analysis of the expert experience-based example study to explore key relationships, it was found that the SDGs with the highest level of connectivity to sustainability requirements are SDG8, SDG12, SDG16, and SDG3. However the most central SDG through the sustainability requirements are SDG3 and SDG8, while the least interlinked is SDG16. These findings are aligned with the principles of Industry 5.0, which emphasizes the need to establish strong, resilient institutions that prioritize worker well-being and promote economic growth and productivity through the integration of digital technologies. Additionally, Industry 5.0 promotes sustainable production and aims to decrease environmental impact in areas such as energy, waste, and water management. However, the focus on SDGs and sustainability requirements can differ for each industry and even country due to the industrial and country-specific requirements and development initiatives.

The most critical Industry 5.0 solutions were identified as Sustainable thinking, followed by Data sharing and transparency, Business process monitoring, and Human-centric management, then Operational and resource efficiency, and Renewable integration. These are also the most central elements considering the linkages through sustainability requirements. Furthermore, Sustainable thinking, Data sharing and transparency, System integration, and interoperability have great driving power and low dependence power which indicates that these are foundations of establishing Industry 5.0 strategies and supports other solutions to be efficient. Therefore, investing in these solutions is fundamental.

According to a recent empirical study, which was performed 15 companies, they also revealed that key enablers of sustainable Industry 5.0 transition by categories are [175]: 1) sustainable corporate culture, communication, management commitment, collaborative networks and strategic aligment which is covering the HCA and STH Industry 5.0 solution; 2) renewable resouces, data transparency and flow, internal innovation and business model development, which is in line with RIN, DST, BOM, CIP; 3) balanced integration that is SII, VUI, INA. Furthermore, according to Yada *et. al.* Industry 5.0 applications can provide better reporting in terms of authenticity, retrospective reporting, customizability, scope of reporting, cost and efficacy [176]. The applications highlighted are in line with our study such as data collection at source, advanced data analytical capabilities (related to RTC), authenticated transactions (related to DST), or enhanced integration across devices and entities (related to SII). Considering these enablers of Industry 5.0 organizational transformation, it aligns with the aspiration of achieving a balanced development of both technological capabilities and human-centric organizational management, and develop solutions focusing on human aspects. In order to emphasize human aspirations, additional two Industry 5.0 solutions, the Operator 4.0 and Human-centric approach have to gain attention. From both aspects, since the former focusing on the technicalities, while the latter on the managerial and strategic aspects of creating an ethical, transparent, learning organizational environment. We must note that each solution can be further decomposed, which is highlighted in the exploration study.

It should be emphasized that investing in digital technologies is essential for organizations to retain competitiveness and satisfy sustainability requirements. Nevertheless, the applicability of such technologies, tools, and methods is reliant upon the specific organizational context and targeted business objectives. Moreover, it is becoming increasingly clear that investing in emerging technologies alone will not suffice; rather, a move towards cross-collaboration will be necessary to attain a shared objective, such as energy-efficient and cleaner production. Achieving such goals necessitates the establishment of digital trust, security, and an organizational culture that supports collaboration.

The presented aspect and method can support organizational strategy-making that centers on Industry 5.0 principles while identifying sustainability requirements and performances on SDGs. In addition, it enables the selection of Industry 5.0-driven tools and techniques to invest in and integrate into organizational processes to

achieve targeted business objectives. Furthermore, allows for the measurement and reporting of organizational performance, and allows benchmarking activities.

Nevertheless, the proposed framework has some limitations that should be considered when interpreting the results. The relationship matrices are partly based on expert judgement, therefore, the resulting rankings should be interpreted as decision-support priorities, not as fixed deterministic orders. A limitation of the current analysis is that formal sensitivity analysis was not performed. In future work, the robustness of the ranking could be tested by varying the weights of sustainability requirements and by systematically modifying the expert-defined relationships.

Overall, the chapter underpins Thesis III by translating sustainability requirements into Industry 5.0 solution strategies at organisational level, thereby bridging the global and regional perspectives of the earlier chapters with concrete decision-support for organizations.

From a cross-level perspective, the organizational-level findings also reveal an implementation gap and related implications that must be addressed at the process level. The proposed QFD- and network-analysis-based framework connects sustainability requirements with Industry 5.0 solution families and supports strategic prioritization at the organizational level. However, the identification of a highly connected or strategically important solution does not demonstrate that the solution can be successfully implemented in a specific production process or that it will automatically improve environmental, social, operational, or economic performance.

This creates an implementation gap between organizational strategy and process-level execution. The QFD matrices indicate what an organization should prioritize, while the network analysis reveals structural relationships and potential synergies, but neither method specifies how existing workflows should be redesigned, which data must be collected, how digital technologies should be integrated into the process architecture, or how the effects of implementation should be measured. These questions require process models, operational data, simulation, system integration, and KPI-based evaluation and are therefore addressed by the data-driven BPM framework in Chapter 5.

A further gap concerns empirical and organizational contextualization. The relationships and priorities identified by the framework are partly based on literature

synthesis and expert judgement and must therefore be adapted to company size, sector, regulatory environment, stakeholder expectations, regional conditions, and technological maturity. Regional readiness indicators from Chapter 3 can provide information on the external enabling environment, while process-level evidence can validate whether the selected organizational priorities generate the intended operational outcomes.

Finally, the framework establishes traceability from global SDG directions and ESG-oriented strategic expectations to organizational development alternatives, but the reverse feedback pathway remains dependent on measurable implementation results. Operational data and process KPIs are required to determine whether organizational interventions actually contribute to sustainability objectives and to refine the QFD relationships and strategic priorities over time.

Chapter 5

Data-driven business process management for Industry 4.0 and 5.0

This chapter moves from the organizational level to the operational/process level, showing how the principles of Industry 5.0 objectives derived from organizational strategycan be translated into data-driven, measurable improvements on the shop floor. It elaborates a practical business process management guideline: from an objective baseline assessment (data collection, performance indicators), through process redesign and horizontal/vertical integration, to deployment and continuous feedback. The framework is illustrated with a CNC production line case study, targeting reduced cycle time, improved quality and resource efficiency, and the creation of a transparent, decision-support KPI structure. The result is a step-by-step guide that links data, technology, and process control to deliver tangible performance gains.

5.1 Introduction

The manufacturing sector highly affects the competitiveness of Europe as it accounts for 16% of Europe's GDP. This sector is responsible for 64% of expenditure with regard to Research & Development in the private sector, and 49% of cost related to innovation in Europe [177]. Industry 4.0 (I4.0) is an emerging phenomenon

that seeks to provide a networked ecosystem which aims to achieve a more efficient and customer-oriented operation, sustainable competitiveness and smart growth. The digital transformation of manufacturing enterprises should result in more efficient business processes. To support this development, this research aims to study how the business process management (BPM) of manufacturing companies should focus on developing I4.0-driven technologies and how business process redesign (BPR) can utilise the advanced tools and methods developed in the Fourth Industrial Revolution. Furthermore, the contribution of the design science approach to the BPM life cycle model is explored to highlight innovative and data-driven process development.

The major features of integrating I4.0 into business management are the real-time capability, interoperability, modularity, decentralization and virtualization as well as the horizontal and vertical integration of processes through ICT (Information and Communications Technology) systems [178, 179]. This digital transformation results in Cyber-Physical Systems (CPSs) [180] that have several potentials to improve the efficiency of manufacturing [181].

Businesses can gain a competitive advantage through this data-driven operation, enable innovation and product life cycles to be shortened as well as predict and respond to market demand in time [182]. The realization of data-driven workflow management, both vertically and horizontally, facilitates collaboration between multiple devices - namely, Machine to Machine (M2M), business management systems and production lines - that is Business to Manufacturing - in others words, Business to Business (B2M), and data sharing between business units (B2B)[183].

The adaptation of these changes requires a new perspective and leads to the need to rethink as well as redesign business processes and models [184], for which BPR in the context of design science research (DSR) is effective. "BPR is an organisational initiative for achieving competitive multi-faceted advantages regarding business processes, in terms of cycle time, quality, cost, customer satisfaction and other critical performance metrics" [185]. DSR contributes to business process redesign through iterative process analysis. DSR is a problem-solving paradigm that supports innovative, knowledge- and data-centric artifacts creation in the form of models, methods, constructs and insantiations [186]. In a I4.0 manufacturing organization context, artifacts are considered to be I4.0 technologies, tools and methods. The concept of DSR can be carried through the whole BPM process life cycle.

Modelling notations are considered as tools of BPR, such as the Business Process Model and Notion (BPMN), Unified Modeling Language (UML), XML Process Definition Language (XPDL), Petri Net, Integration Definition Method (IDEF0 and IDEF3) and Business Process Execution Language for Web Services (BPEL4WS) [187]. However, in the following, only the BPMN is discussed more precisely as it is mainly for business process modeling and its structure is clearer and easier to use [187]. BPMN creates a standardised bridge over the gap between business process design and process implementation [188]. This technique promotes the automated execution of workflows and provides a comprehensive model, the graphical notion of which is a Business Process Diagram (BPD) [188]. An adequate BPMN model is needed to gain an easily applicable data-centric workflow optimisation. The defined processes in BPMN can be further improved and optimised by applying the business process simulation approach [189]. Simulation techniques allow for complex data-intensive processes to be analysed and diverse scenarios evaluated [190]. However, the potential of digital twins [191] provides a new level of efficiency in terms of adapting and controlling large complex business processes [192].

While the primary objective of Industry 4.0-driven Business Process Management is to improve operational performance through digitalization and data-driven decision-making, these developments also create opportunities to support sustainability objectives. Recent Green BPM research emphasizes that sustainability should be integrated throughout the entire BPM life cycle by embedding environmental and social considerations into process identification, analysis, redesign, implementation, and continuous monitoring rather than treating them solely as reporting outcomes [193, 194]. Consequently, besides their operational benefits, Industry 4.0 technologies can also provide measurable sustainability co-benefits, such as improved resource efficiency, reduced material waste, lower energy consumption, enhanced workplace safety, and more transparent environmental performance monitoring. These sustainability co-benefits are summarized together with the BPM life-cycle phases in Table 5.1. However, they should not be interpreted as automatic consequences of digitalization but as measurable outcomes that depend on the selected technologies, organizational capabilities, and appropriate sustainability-related performance indicators [195, 196].

The purpose of this research is to develop a methodology to improve data-driven process development, resulting in an evidence-based decision support tool in BPM.

It aims to facilitate digital transformation and the conversion of production into flexible manufacturing systems, therefore, improving business agility.

Organisational I4.0 developments require a clear understanding of the 'as-is' state [61]. Maturity models highlight the strengths and weaknesses [197]. Maturity models measure the readiness to adapt digital transformation and data-driven solutions. The adaption of the new technologies and strategic operational processes requires the redesign of the business processes. The successful realization of the I4.0 concept demands the applications of ICT and automation technologies as well as the related standards and ontologies. Trends in I4.0 define the need for interoperability amongst actors, sensors, and heterogeneous systems [198]. Standards, formal models and ontologies play a significant role in the I4.0 system environment, for which enforcement, linked data should rely on systematically enriched information [199].

Such I4.0 standards describing reference architectures for smart factories are the ISA-95 [149], ISA-S88 [200] or RAMI4.0 [201] models. Standards Ontology describes the characteristics as well as relations between standards and organizations for publishing standards in addition to standardization frameworks in the context of I4.0 [202]. Ontologies can be considered as the next generation of standards for connecting information [199]. To develop interoperability, the Industrial Ontologies Foundry (IOF) works with the governmental, industrial and academic sectors as well as standards organizations by creating a set of core and open reference ontologies covering the entire domain of digital manufacturing [203]. Therefore, semantic technologies are essential in the field of ICT and automation technology (AT) to exploit and connect information between and within companies [204]. The development of I4.0-induced business processes management based on standardized domains can result in a better served and more transparent structure to manage the robustness of the system with a high degree of reliability.

The overall purpose of this research is to provide a data-driven method for the analysis and development of Industry 4.0 solutions based on business process modeling and simulation.

The proposed methodology is based on the improvement of the BPM life cycle with the integration of a data-driven application. The phases of the BPM life cycle are connected with diverse data-based technologies, tools and methods to facilitate its successful adaptation and efficient operation. The potential in data

analysis is highly connected to this concept, therefore, this linkage is highlighted by providing an overview of the integrability of CRISP-DM/ML standards into the BPM life cycle. This concept is demonstrated through the development project of a Hungarian assembly and engineering company that produces customized and fully autonomous factory units. The illustrative example demonstrates how the redesign of a production line consisting of Computer Numerical Control (CNC) machines can be supported by BPM and BPR tools.

The aforementioned I4.0-induced business process transformation models, methods, and support tools are explored in the following sections.

- In Section 5.2 the strategic business process transformation for Industry 4.0 is discussed.
- Section 5.3 highlights that the BPM life cycle of I4.0 technologies should intensively utilise data-driven process development tools so that development projects can be efficiently supported by the integration of the standards of data mining (DM) and machine learning (ML) development projects into the BPM life cycle.
- Based on the critical analysis of BPM, I4.0, and CRISP-DM/ML standards as well as methods, a detailed methodological guideline has been formulated for managing business processes in the field of I4.0 in Section 5.4.
- Some details related to the applicability of the method are also presented in an illustrative case study in Section 5.5.

5.2 Strategic business process transformation for Industry 4.0

The realization of digital solutions is a long-term commitment towards the evolutionary path of I4.0 [205]. Existing business processes must be developed within the organization as well as business models [206]. Even though diverse implementation strategies exist for realizing I4.0 within a company, they all seek to achieve transparency, visibility, interconnectivity and efficiency. Ref. [206] defines a road map for implementing I4.0 in terms of enterprises, the major step of which are

analysis (understanding the I4.0 concept and the maturity of organization - 'as-is' state), targets (define areas of action, evaluate conditions - redesign processes), realization (prepare decisions and define projects - 'to-be' model and implementation strategy), while the implementation strategy to achieve value-added networks is assessed in Ref. [205]. Its core components are defined as research and innovation, reference architecture and standardization as well as the security of networked systems, which are accompanied by the creation of legal framework conditions.

The six steps for implementing strategic development are shown in Figure 5.1. The concept shows how maturity models are enable to foster business transformation and allows phases of the BPM life cycle to be linked to digital and technological domains as well as supports the integration of data analysis into the transformation framework [5]. The BPM life cycle is a comprehensive concept which enables the organizational transformation of processes to be managed [207]. Its phases are the following: process identification, process discovery, process analysis, process redesign, process implementation, process monitoring and process control.

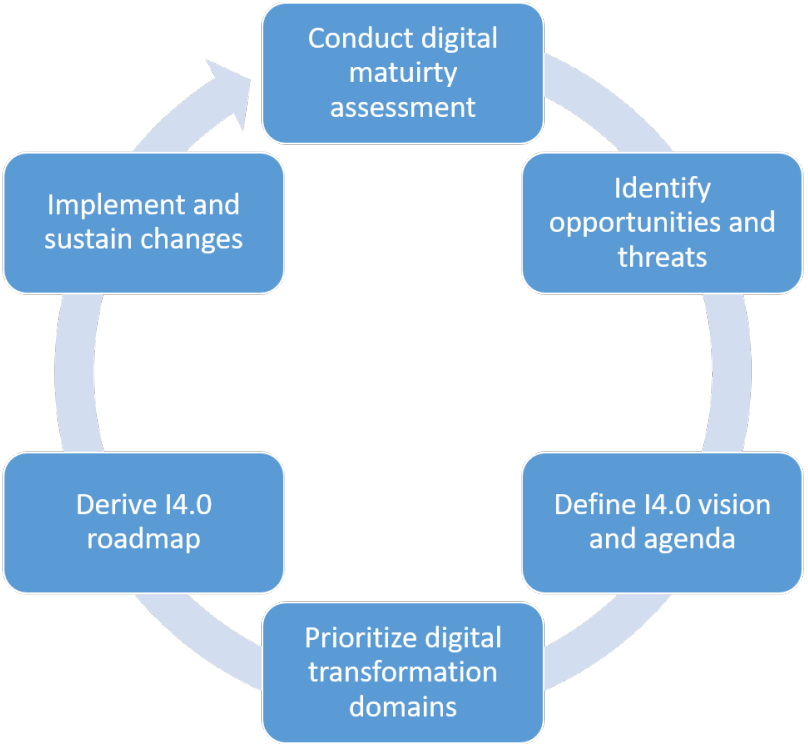


FIGURE 5.1: Recommended steps for implementing strategic development [5]

The development cycle of implementing strategic changes includes [5]:

1. The digital maturity assessment of an organization, which is an essential step to derive a common understanding of the 'as-is' state of processes (maturity models and process identification).

2. The exploration of possible threats and opportunities is a foundational step towards redesigning our processes (process identification and discovery).

3. The development of an 'ideal' vision and agenda for creating the 'to-be' goal model of an organization (process analysis and redesign).

4. "Development domains should be prioritized because the creation of Industry 4.0 systems is a complex activity, since the very nature of this concept implies that it affects all business and technical sub-processes" [208] (process analysis and redesign).

5. An I4.0 road map can serve as the 'to-be' model of the redesigned processes, which can facilitate the transformation process coordinating the actions (process redesign).

6. The realization and implementation of the derived I4.0 road map (process implementation and monitoring).

With regard to research projects, information technology-based design science research approach is crucial as it is focusing on developing knowledge and support innovative problem solving though atrifacts as models and methods. DSR identifies the problem and its impact, thus reveal potential redesign areas. DSR iterates how would a better artifact (e.g. I4.0 solutions) accomplish in the problematic environment, develops and design a solution, then apply it and measure performance metrics to access effectiveness of the redesigned process. Finally communication of the results is essential for further researches [209]. DSR is a research paradigm with a focus on generating hypotheses on how the future could look ('to-be') and iterates solutions for the redesign. It is initially filtering them to remove hypotheses that are not worth pursuing. "By widening the employment of DSR, the information science discipline can acquire a leading position in the field of practice" [210, 211].

The aforementioned concept covers and facilitates BPM as well as the integration of digital technologies, tools and methods for redesigning and implementing I4.0 projects in addition to transformed business processes. The description of the

BPM life cycle model and its technology-driven support as well as the possible data-analytic connection to this concept is given in Section 5.3.

5.3 Data-driven development of business process management life cycle

This section discusses the foundations of BPM and the technology alignments to support efficient governance for process-oriented organizations as well as highlights the benefits of utilizing the integration of data-driven applications and standards into the BPM life cycle as well as considering sustainability co-benefits of the transformation.

Section 5.3 defines how I4.0-driven technologies, tools and methods can be utilized through phases of the BPM life cycle, while Section 5.3 provides an insight into the potential integration of data mining and machine learning standards (CRISP-DM/ML) into the BPM life cycle.

Improvement of the BPM life cycle with the integration of technology alignments

Business processes can be considered combinations of interconnected events, activities and decision points that include many actors and information carriers. Altogether, they contribute to a value-added result for at least one customer [212]. Due to constant digital transformation, managing business processes is no longer a choice but a necessity to remain competitive and productive in the market [213]. Although the role of digital technologies in transforming business processes seems to be under-investigated [214].

BPM is a comprehensive system for managing and transforming organizational operations through business process modeling, execution, and evaluation, with agility and operational performance goals[207]. To monitor and continuously develop business processes, BPM utilizes several methods, policies, metrics, management practices, and software tools [213]. In Figure 5.2, the model of a BPM life cycle is shown.

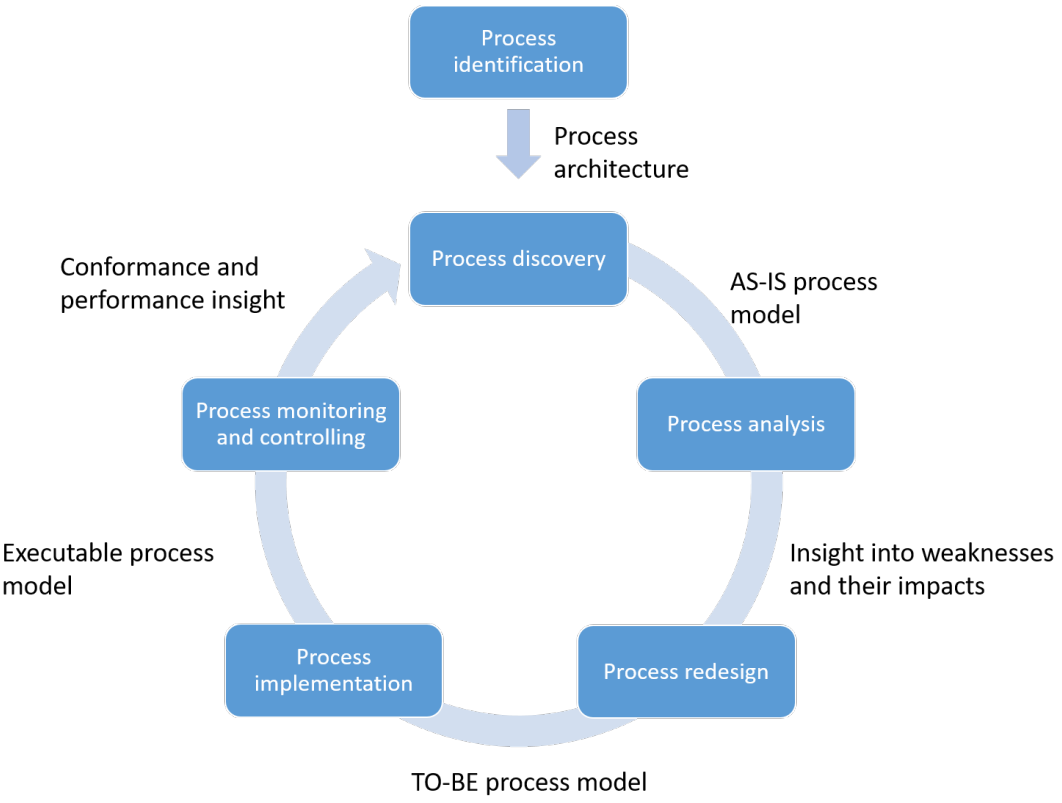


FIGURE 5.2: A model of the Business Process Management (BPM) life cycle (Source: Ref. [6])

Technological developments and digital innovation make it necessary for BPM to be thought through afresh. "Emerging technologies have capabilities to reshape business process management from its traditional version to a more explorative variant" [215]. Ambidextrous BPM mixtures consist of two aspects: exploiting the benefits of existing technologies (i.e., exploitative BPM), while simultaneously exploring the benefits of new IT (i.e. explorative BPM) [216].

The innovation- and data-driven perspectives of transforming business models and processes and the technological tools and methods to support BPM cannot be neglected. "Technology is not the goal, but the instrument and process excellence is the driver to introduce new technologies in the operations" [217].

The digitization of manufacturing enterprises creates the basis for I4.0 principles such as interoperability, decentralization, virtualization, real-time capability, service orientation, and modularity [213]. Organizations seek to be stable, flexible and capable of adapting to changes, while organizational stability provides agility and innovation platforms [218]. Continuous improvement in terms of managing

business processes requires the combination of BPM with digital leadership [218], to derive a maturity level that can help to accomplish capabilities for organizational success [219]. In order to achieve real-time capability, cloud computing offers immediate access to hardware resources as well as lowers IT barriers and opens up new ways to innovate [220]. Machine learning standards, tools, methods and approaches can facilitate the automation and optimization of processes as well as support BPM through new algorithms [221]. In the context of BPM, Information Systems (IS) supporting the processes produce the structured data, i.e., logs, which are analyzed with process mining techniques used to discover processes and bottlenecks, check compliance, and propose process improvements [222, 223].

Furthermore, a direct link between goals, objectives and strategies regarding key performance indicators (KPIs) is needed [224] to support evidence-based decision-making through the BPM life cycle.

In Table 5.1, Industry 4.0-induced, data-driven applications, tools, and methods are identified and mapped to the phases of the BPM life cycle, demonstrating how digital technologies can facilitate more efficient evidence-based decision-making. The table includes a brief definition of each BPM life cycle phase based on Ref. [212], the corresponding supporting tools that enhance each phase, their operational benefits, and representative references. In addition, the table explicitly identifies the potential sustainability co-benefits associated with each phase. These co-benefits are derived from the sustainable manufacturing and Green BPM literature and illustrate how process transparency, analytics, simulation, automation, and continuous monitoring can contribute to improved environmental and social performance. However, these benefits should not be interpreted as automatic consequences of digitalization; their realization depends on context-specific sustainability objectives, system boundaries, baseline conditions, and measurable performance indicators.

TABLE 5.1: Industry 4.0-induced applications, tools and methods supporting the phases of the Business Process Management (BPM) life cycle and their potential sustainability co-benefits. (Source: based on Ref. [6])

BPM life cycle phase	**Definition**	**Supporting tools**	**Benefits**	**Sustainability co-benefits**	**References**
Process identification	Processes relevant to the problem being addressed are identified, delimited, and interrelated. The outcome is a new or updated process architecture that provides an overall picture of the organization's processes and their relationships.	Maturity models; BPMN; process mining; cloud computing; digital twins.	Transparency; virtualization; real-time capability; interoperability.	Identification of environmentally and socially relevant processes, activities, and system boundaries. Sustainability-oriented process architectures can reveal where energy, materials, water, waste, emissions, occupational risks, and data-intensive activities enter the value-creation system. Potential indicators include energy- and material-relevant processes, waste-generating activities, emission sources, and occupational-health-and-safety exposure. [193, 194, 195]	[225],[226],[227], [228], [229], [230]

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Table 5.1 – continued from previous page

BPM life cycle phase	Definition	Supporting tools	Benefits	Sustainability co-benefits	References
Process discovery	The current state of each relevant process is documented, typically in the form of one or several "as-is" process models.	Process mining; cloud computing; digital twins.	Transparency; virtualization.	Event logs and digital twins can reveal the actual use of resources and expose unnecessary transport, waiting, rework, machine idling, repeated processing, and avoidable data transfers. Linking process data with energy, material, waste, emission, and operator-related attributes creates a sustainability baseline. Potential indicators include energy per process instance, material loss, idle time, rework frequency, transport distance, and waste per product. [193, 194, 196]	[228], [229], [230], [231]

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Table 5.1 – continued from previous page

BPM life cycle phase	Definition	Supporting tools	Benefits	Sustainability co-benefits	References
Process analysis	Issues associated with the "as-is" process model are identified, documented, and, whenever possible, quantified using performance measures. The issues are prioritized according to their potential impact and the estimated effort required to resolve them.	Big-data analytics; KPIs; bottleneck analysis; cloud computing; artificial intelligence; process mining; process-model repair.	Transparency; interoperability; real-time capability; interconnectivity.	The conventional time–cost–quality perspective can be extended with environmental and social indicators. Data analytics and process mining can identify energy- and material-intensive variants, emission hotspots, rework loops, abnormal consumption, and safety-relevant deviations. Potential indicators include energy and carbon intensity, scrap and rework rates, water use, material yield, idle time, hazardous exposure, and ergonomic workload. [193, 232, 195, 194]	[229], [230], [233], [234], [235], [236], [237], [238],

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BPM life cycle phase	Definition	Supporting tools	Benefits	Sustainability co-benefits	References
Process redesign	Multiple change options are analyzed and compared using the selected performance measures. Process analysis and redesign proceed iteratively until the most promising options are retained and combined into a redesigned "to-be" process model.	Optimization techniques; standards; ontologies and semantic models; simulation and modelling techniques.	Transparency; interoperability; interconnectivity; virtualization.	Simulation and multi-objective optimization enable alternative process configurations to be compared before implementation. Sustainability criteria can be included as objectives or constraints, for example by minimizing energy, material use, waste, emissions, transport, or ergonomic burden while maintaining throughput and quality. Potential indicators include predicted energy demand, carbon emissions, material yield, waste generation, resource utilization, cycle time, and operator workload. [196, 232, 195, 239]	[190], [240], [241], [242], [243], [244], [245], [246], [247] [248], [249], [250]

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Table 5.1 – continued from previous page

BPM life cycle phase	Definition	Supporting tools	Benefits	Sustainability co-benefits	References
Process implementation	The changes required to move from the "as-is" process to the "to-be" process are prepared and performed. Implementation covers organizational change management and process automation, including the development or deployment of IT systems supporting the redesigned process.	RPA; IoT; CPS; cloud computing; digital twins; cloud manufacturing; simulation and modelling; collaborative or autonomous robots; AI; augmented reality.	Interoperability; interconnectivity; real-time capability; virtualization.	IoT, CPS, AI, and digital twins can support closed-loop resource control, predictive maintenance, adaptive scheduling, and automated quality assurance. These mechanisms may reduce downtime, defective production, premature component replacement, energy use, and material waste. Collaborative robotics and augmented reality may also improve safety, ergonomics, and knowledge transfer. Potential indicators include energy per good unit, downtime, component lifetime, scrap rate, incident frequency, ergonomic risk, and training coverage. [196, 232, 195**?** , 239]	[251], [252], [253] [254], [255], [256], [257]

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Table 5.1 – continued from previous page

BPM life cycle phase	Definition	Supporting tools	Benefits	Sustainability co-benefits	References
Process monitoring and controlling	Once the redesigned process is running, relevant data are continuously collected and analyzed to determine performance against objectives. Bottlenecks, recurring errors, and deviations are identified, corrective actions are initiated, and the BPM cycle is repeated when new issues arise.	IoT; CPS; cloud computing; MES; simulation and modelling; AI; augmented reality; process mining; digital twins.	Interoperability; interconnectivity; real-time capability; virtualization.	Continuous monitoring allows sustainability performance to be managed as a process property rather than only as a reporting outcome. Resource and environmental KPIs can be linked to machines, products, shifts, and process variants, enabling early detection of abnormal energy use, leaks, scrap, declining equipment efficiency, unsafe states, and rebound effects. Potential indicators include energy and carbon intensity, material yield, water use, waste, emissions, equipment condition, deviations, near misses, and safety events. [193, 194, 195**?** , 239]	[230], [233], [256], [258] [259],[257]

In the following, the phases of the BPM life cycle are explored with a significant focus on supporting digital technologies, tools and methods as well as the related sustainability co-benefits.

The **process identification** phase can be supported by organizational maturity models, digital technologies and tools such as process mining, the Business Process Model and Notion (BPMN) and the Digital Twin of an Organization (DTO). Conceptualizing and measuring the maturity of an organization or a process facilitates the understanding of business architectures, therefore, allows the 'as-is' state of processes to be detected [225]. BPMN 2.0 is a standard notation for modeling business processes [260]. The flat control flow perspective, sub-processes, data flows and resources can be integrated within one BPMN diagram, which is interesting from the process miners' point of view [226]. BPMN serves as a representational of modeling processes and opens excellent perspectives for the applicability of process mining. "Discovered process models become available and understandable, and the models can be imported/exported from/to any BPMN modeling tool and executed, process mining techniques can be easily integrated to the existing suites (BPMN serves as an interface in this case). Moreover, BPMN models allow for the combination of different perspectives varying from control flow (including sub-processes) to the perspective of resources" [226]. Process mining is an innovative tool supporting the digital transformation of companies by providing a holistic insight into actual processes and complexities, therefore, allowing the identification of inefficiencies and effort drivers [227]. Process mining techniques should support workflow models such as BPMN [230]. Models extracted from event data provides a purposeful abstraction of reality. Therefore, due to the dynamic nature of processes, process mining should be considered as a continuous process to create a "living and learning process model" [230]. The next level realization of current processes is utilizing digital twins. Digital Twin of an Organization (DTO) serves as a virtual copy of processes, therefore, promotes the understanding of process architectures [229]. A DTO is "a dynamic software model of any organization that relies on operational and/or other data to understand how an organization operationalizes its business model, connects with its current state, responds to changes, deploys resources and delivers expected customer value" [228]. From a sustainability perspective, process identification also establishes the organizational and system boundaries within which environmental and social impacts are assessed. Identifying resource-intensive processes, emission sources, material

flows, and human-related activities at this stage provides the basis for integrating sustainability objectives into subsequent BPM phases [193, 195].

Process discovery can be facilitated by process mining and the perspective of a DTO. Process mining enables businesses to analyze business processes based on digital traces captured in event logs. It is an effective tool to visualize the 'as-is' process flows and check their actual conformance [229]. A DTO provides a virtual interpretation of actual process flows [228], therefore, allows a punctual 'as-is' model of processes to be created. Furthermore, the Business Process Catalog and Classification Scheme (BPCCS) can foster the discovery of business process elements by providing the shared vocabulary of various business process models (e.g. activities, sub-processes, roles) [261]. "Combining Robotic Process Automation (RPA) with the popular BPM approach poses a useful strategy as the 'as-is' process is optimized first". Subsequently, the RPA procedure is then deployed on the optimized process to reach its full automation potential [231]. Beyond reconstructing the actual process flow, process discovery can reveal how resources are consumed in practice. By enriching event logs with energy, material, waste, or emission-related data, sustainability hotspots, unnecessary transportation, rework, and idle times can be identified, providing a measurable baseline for further improvements [194, 193].

The phase of **process analysis** can be improved by process mining, big data analytics, KPIs, artificial intelligence (AI) or diverse analyzing techniques such as bottleneck analysis. Big data management and analytics cannot be neglected in terms of process analysis. Big data analytics allows business processes to be measured and knowledge to be directly translated into decision-making and performance [262]. Big data enables internal processes to be streamlined by reducing the bottlenecks, therefore, increasing the efficiency of processes [237]. Identifying bottlenecks is essential as it affects the operation of the whole system. The bottleneck of a manufacturing system refers to a subsystem that limits the capacity of the entire system. Overall Equipment Effectiveness (OEE) can be used as a KPI that indicates a system's overall capacities and subsystems. However, the lowest OEE may not provide information about bottlenecks because other subsystems can cause them. To overcome this drawback, the standalone OEE (OEE_{sa}) was formed that reveals the true capability of the system, which is partially hidden due to external factors [236]. KPIs measure performance in terms of business goals, typically reflecting the time, cost and quality domain. A direct link exists between

KPIs, objectives, and strategies [224]. In terms of evaluating 'as-is' processes, registered KPI values can be verified by process mining to determine deviations from KPI target values, therefore, facilitate the redesign phase [263].

Process mining enables structured data from a process perspective to be analyzed. In some cases, it allows KPIs to be modified in ways that optimize the output to facilitate data-based root cause analysis, which enables errors to be directly connected to relevant process steps as well as identifies unwanted effects [233]. Process mining techniques enable to observe behaviour (e.g. event logs) to modeled behaviour (e.g. BPMN model), therefore, detect and diagnose differences between observed and modeled behaviour [238]. Process Model Repair uses a reference process model and an event log as an input. If the model cannot fully explain the observed behaviour, these parts of the model which are not consistent with the observations can be repaired using this technique [238]. Furthermore, the constantly improving technology fosters the continuous development of business processes; thus, business process redesign can be considered as a process enhancement operation (process model repair). Process mining can be further aided by AI, which offers possibilities in predictive process mining [233]. Predictive process mining plays a significant role in business scenarios as it enables the next activity of a running process to be identified in advance. Therefore, it can foster "optimal management of resources and promptly trigger remedial operations to be carried out" [235]. The data gathered about the execution of the processes provides information about decision patterns, performance, or control-flow provides, which information can be utilized in simulation models to perform a new complex process model [230]. The comprehensive twin of all process activities and complexities provides the strategic management of an organization with insights based on facts. Strategic directions such as digital transformation programs become measurable and thus easier to manage [229].

Process analysis can be extended beyond traditional operational KPIs by incorporating sustainability-related indicators such as energy consumption, greenhouse-gas emissions, material yield, water consumption, and occupational safety. Combining process mining with these indicators enables the identification and prioritization of sustainability-related process inefficiencies [195, 232].

The **process redesign** phase of the BPM life cycle can be improved by I4.0-induced technologies, models and tools, in addition to optimization techniques, standards, ontologies and semantic models, as well as simulation and modeling

techniques. A major aspect of I4.0 is to provide a coherent approach for adapting semantic communication between intelligent systems. To redesigning businesses according to this approach, a communication model is needed for which ontologies can provide a solution by formalizing the knowledge of smart manufacturing in an interoperable way. "An unambiguous, semantic-based knowledge representation of concepts for smart manufacturing domain is required to ensure a coherent and effective human-robot collaboration" [241]. Industry practitioners can use these ontologies to conceptualize implementation scenarios [242]. Indeed, as every scenario considered within the framework of I4.0 includes different entities which communicate and cooperate, the main role of the presented ontological standard is to facilitate that exchange [241]. According to the domains of I4.0, Factory 4.0 or smart manufacturing, both the perspectives of business and production are involved. "As I4.0 relies heavily on robotic agents which have to evolve and perform the main operations in smart manufacturing environment and which are solicited to communicate with human operators, customers, or with diverse distributed partners. The standardization of knowledge representation is a key element facing I4.0 development and is required to be addressed quickly and efficiently to avoid accumulated difficulties at later stages of the development" [241]. Therefore, ontological standardization regarding I4.0 mainly relies on IEEE 1872-2015 - Standard Ontologies for Robotics and Automation [243] which can be extended by specific ontologies. These ontologies, for example, the Core Ontology for Robotics and Automation (CORA), Ontology for Autonomous Robotics (ROA), Ontology for Robotic Architecture (ORArch) or Ontology for Industry 4.0 (O4I4). During process redesign, the architecture of the 'to-be' process model is developed, which in the I4.0 environment cannot neglect the connection between hardware and software. This viewpoint can be supported by ORArch that elaborates on how hardware and software can be represented together in mixed architecture descriptions [241], while O4I4 is a business-focused ontology [241].

Due to the dynamic nature of the business environment, changes in workflow models of processes are becoming increasingly common. "Process mining application provides a visual and fact-based proof for automation capabilities and enables prioritization of activities" [258]. Goal-oriented ('to-be') dynamic workflows seek to provide flexibility concerning the execution of business processes. "BPMN or similar languages must continue to be the primary instruments for defining a workflow" [244]. In general, optimization procedures still do not support full automation, hence automated optimization solutions are in demand, covering the

monitoring, identification and modification of process structures [245]. For modeling processes in Cyber-Physical Systems (CPS), the BPMN4CPS model has been proposed [250].

The extension of BPMN is based on the simulation of Cyber-Physical Production Systems (CPPS) in terms of reconfigurability, adaptability and reliability. This approach relies on the principles and standards of Model-Driven Architecture (MDA) to improve automation and customization [249]. Ref. [190] presented a largely automated business process modeling and simulation approach based on BPMN. This approach "first annotates the BPMN model with what is necessary to make the model executable (i.e., performance parameters, execution resources, and expected workload), and then automatically maps the annotated model into simulation code ready to be executed" [190]. Furthermore, the effective implementation of production goals can be achieved by the combination of manufacturing process models. "To accomplish this, a workflow control engine needs to be designed and standardized respectively" in IIoT Systems that apply the Arrowhead Framework [248]. IIoT Systems that apply the Arrowhead Framework addresses how BPMN and Coloured Petri Nets (CPN) [264] can be implemented in the Arrowhead Framework, which is an IIoT (Industrial IoT) framework that dynamically and flexibly supports automated manufacturing processes following I4.0 expectations [247]. Furthermore, Robotic Process Automation (RPA) is an emerging technology to automate business processes that are driven by user interaction with software systems [265]. The integration of RPA into BPM allows their technologies to be connected and systematic methods combined [266].

During process redesign, sustainability objectives can be incorporated together with conventional optimization criteria such as cost, time, and quality. Simulation, semantic models, and optimization techniques enable alternative process configurations to be evaluated with respect to resource efficiency, waste reduction, carbon emissions, and human-centred working conditions before implementation [196, 232].

The **process implementation** phase of the BPM life cycle has much potential to be supported by developing technologies and models. In addition to RPA, emerging phenomena include collaborative and autonomous robots, cloud manufacturing, IoT, Digital Twins, simulation and modeling, and the umbrella term of AI. Cloud manufacturing is a networked, intelligent manufacturing model that integrates IoT, the Semantic Web, cloud computing, high-performance computing

and informatized manufacturing to derive a reliable, highly efficient, and quality service for the whole manufacturing life cycle [251]. Cloud manufacturing should be integrated into the BPM life cycle to support business process evolution and adaptation as well as automate this procedure using the Business Process Cataloging and Classification System (BPCCS) [252]. In terms of improving the design and implementation of BPM, a sensor-based IoT network technology can aid this process [253]. IIoT further empowers companies to adopt data-driven strategies and solutions. Being flexible and adaptive to changes in business processes, this paradigm transform industries into cyber-physical production systems [254]. Furthermore, the process-based framework of self-adaptive workflows for CPS ensures agility and autonomy [255]. Implementing Enterprise Resource Planning (ERP) in an organization, the phases of the BPM life cycle must be continuously managed and monitored. According to an Indonesian case study, leading companies "implementing ERP for more than five years, obtained high scores for BPM implementation. They perform well in terms of process identification, implementation, monitoring and control, but are weak in process discovery and redesign, mainly because they do not optimally use specific tools for process modeling and there is a lack of process governance" [256]. The implementation of Robotic Process Automation (RPA) provides a virtual workforce to automatize manual, repetitive and error-prone tasks, the solutions of which will lead to the concept of socio-cyber-physical work systems [267]. The digital replica (digital twin) of the system can be efficient to test and continuously monitor the changes in business processes. Digital twin (DT) is an emerging technology used in intelligent manufacturing, which is the digital copy of a physical system and captures its attributes and behaviours in real-time and predicts (simulate) system failures. The implementation of digital twins enables us to gain an understanding of how the physical system would operate after implementing changes due to business process redesign [257].

The implementation of IoT, cyber-physical systems, digital twins, AI, and predictive maintenance can contribute to sustainability by reducing unnecessary energy consumption, minimizing material waste, extending equipment lifetime, and improving workplace safety. Nevertheless, these benefits depend on the appropriate deployment and operation of digital technologies within the given industrial context [196, 195].

The **process monitoring and controlling** of the whole life cycle is essential for the successful operation. This phase of the BPM model spans the whole life cycle,

not only the monitoring of the results but continuous data collection and model analysis. These activities can be highly supported by data-driven technologies, AI and ML functions, CPS and simulation, as well as process mining or digital twin technologies. Process mining can be used as a "monitoring tool in production that allows data-based, fast decisions. These can help to reduce rework, improve the quality of our products, and reduce production costs" [233]. Process mining further allows the visual and fact-based proof of automation capabilities, prioritizes activities, and supports process automation. Successful process automation demands knowledge about automation potential, effective training of the robots and continuous monitoring of their performance. [258]. Business process automation must be continuously managed and monitored [256]. Regarding manufacturing companies, trends have shifted towards individualized mass production, which presents challenges in achieving interoperability between physical and digital systems concerning the intelligent organization of resources. To manage this, a digital twin-driven Manufacturing Cyber-Physical System (MCPS) for parallel controlling of a smart workshop under a mass individualization paradigm can be a solution [259]. The continuous monitoring and prediction of production systems are critical features for which intelligent manufacturing systems provide a real-time solution resulting in lower cost, increased flexibility, higher productivity, and better quality [268]. The extension of DT is the Hybrid Digital Twin (HT), which "recognize, forecast and communicate less optimal (but predictable) behaviour of the physical counterpart well before such behaviour occurs. An HT integrates data from various sources (e.g., sensors, databases, simulations) with the DT models and applies AI analytics techniques to achieve higher predictive capabilities while at the same time optimizing, monitoring and controlling the behaviour of the physical system. An HT is typically materialized as a set of interconnected models, achieving symbiosis among the DT models" [257]. Beyond DT and HT, the concept of cognitive digital twin (CT) encompasses some forms of cognitive capabilities, which enable improved data-, knowledge- and experience-based automatic decision making. CT overarch the whole life cycle of the system [257].

Continuous monitoring enables sustainability performance to be managed alongside operational performance. Real-time monitoring of energy consumption, material efficiency, emissions, equipment utilization, and occupational safety indicators supports continuous improvement and provides objective evidence for evaluating the sustainability impacts of process changes [193, 194].

Standards with regard to business analytics - the CRISP-DM/ML framework

A vast amount of heterogeneous data is generated during organizational operation, enabling a business insight at a higher level to be gained. Big data analytical techniques must be implemented directly into business processes to successfully recognize, analyze and redesign organizational processes as well as outperform competitors [269]. According to a report by Gartner, organizations are motivated to use data mining, AI and ML to improve and automate tasks. Furthermore, they are expected to double the number of machine learning projects within a year [270]. Data mining and machine learning aim to identify patterns and relationships hidden in a vast amount of heterogeneous data to support the decision-making process. However, the major differences between DM and ML are hidden in the time frame and level of automation. Since DM identify patterns on existing data, while ML predicts future outcomes on the 'pre-existing' data due to the initially given rules, and the learning and refining are automatic without human intervention [271]. Businesses can improve their data mining analytics with machine learning algorithms to improve efficiency [272]. In many cases, organizations rely on models closely related to ML, such as the Cross-Industry Standard Process for Data Mining (CRISP-DM), grounded on industrial data mining experience. However, CRISP-DM has two significant drawbacks as "not cover the application scenario where an ML model is maintained as an application" and "lacks guidance on quality assurance methodology" [273]. Regarding Ref. [273], a Cross-Industry Standard Process for Machine Learning is defined using quality assurance methodology (CRISP-ML(Q)). The methodology defines quality as it is "not only defined by the product's fitness for its purpose but the quality of the task executions in any phase during the development of an ML application" [273]. It extends the CRISP-DM principles of ML purposes as it focuses on "technical tasks needed to produce evidence that the development process of a given ML application is of sufficient quality to warrant the adoption into business processes". The CRISP-ML model is shown in Figure 5.3 and consists of six phases: business and data understanding, data preparation, modeling, evaluation, deployment and monitoring, and maintenance. The sequence of these phases can vary and the arrows indicate the most frequent and important dependencies between phases. Iteration and the revisiting of previous steps are needed until success is achieved or criteria are met [273].

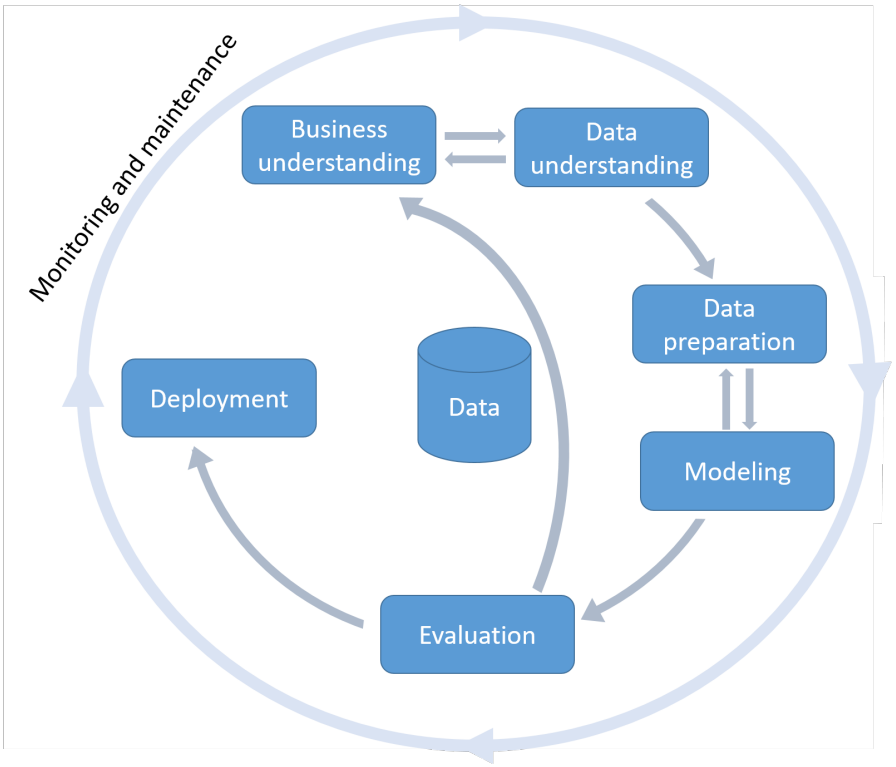


FIGURE 5.3: The process model of CRISP-DM extended by an overarching monitoring and maintenance phase (Source: Ref. [6])

Standard processes during business process management are needed, and the increase in the number of I4.0 applications enables a highly automated environment with machine learning subsidies to be created. Therefore, the CRISP-ML(Q) integration into the BPM life cycle is discussed to derive a methodology suitable for industrial parties to manage and support business processes in the I4.0 environment efficiently. Table 5.2 describes that the key features of CRISP-ML(Q) can be fitted into the phases of the BPM life cycle well as defines the outputs of each phases [274].

TABLE 5.2: Intertwining features between CRISP-ML(Q) and the phases of the BPM life cycle ensuring the suitability of integration (Source: Ref. [6])

CRISP-ML(Q) phases	**BPM life cycle phases**	**Features**	**Outputs**
Business understanding	Process identification	Creating an overall process architecture, defining business scope and objective.	Determined business background and objectives.
	Prodess discovery	Defining 'as-is' state to assure feasibility.	Assessed situation, detemined data mining/ machine learning goals and success criteria.
			Produced project plan, initial assessment of tools and techniques.
Data understanding	Process analysis	Collecting and verifying the data quality regarding the structured issues and, finally deciding upon whether the project should be committed.	Collected initial data, described, explored and verified data.
Data preparation	Process analysis	Producting a data set for the modeling/design phase.	Created dataset and its description (selected, cleaned, constructed, integrated, formated data).
Modeling	Process redesign	Creating models that satisfy the given constraints and requirements ('to-be' process model).	Selected modeling technique, generated test design, built and assessed model.
Evaluation	Process analysis	Design and analysis are intertwinned and as new change options are proposed, they are analyzed using process analysis techniques. The performance, robustness and explainability must be evaluated.	Evaluated results, reviewed process.
	Process redesign		Determined further steps.
Deployment	Process implementation	Preparations to move from the 'as-is' process to the 'to-be' process are made and the transformation is carried out. Before rolling out a model to all, it is best practice to deploy it first to a small subset and evaluate its behaviour in a real-world environment (called canary deployment).	Planned deployment, produced final report and reviewed project.
Monitoring and maintenance	Process monitoring and control	Monitoring and maintenance processes to assure quality performance and identify corrective actions. The model has to adapt to changes in the environment.	Planned monitoring and maintenance plan.

The management of business processes by supporting digitization and automated processes via AI has great potential for organizations. The consistent redesign of processes to implement the I4.0 environment is critical, as is the opportunity for companies to use their data and make intelligent, profitable and real-time decisions [221]. ML-related standards, tools, methods, and approaches promote process automation and optimization as well as facilitate BPM through new algorithms and independent learning through continuous data analysis [221]. Automated optimization solutions are required, covering monitoring, identification and modification of the process structure [245]. A crucial element of the redesign of business processes according to the concept I4.0, the standardized knowledge representation [241]. In terms of I4.0 and the intelligent manufacturing environment, ontological standardization relies highly on robotics and automation to facilitate information exchange for communication and cooperation.

Industrial data mining and ML-related process standards (CRISP-DM/ML) are comprehensive process models for data mining/machine learning that provide a foundation for developing a specialized process model ('to-be') and define steps to achieve it [31, 273]. These steps are highly interrelated to the phases of the BPM life cycle, as is highlighted in Figure 5.3. Integrating the constantly developing technologies and diverse standards into the BPM model facilitates I4.0 fitting as well as highly flexible, interconnected and agile business processes. Furthermore, BPMN models describing both 'as-is' and 'to-be' process models ensure transparency. Simulation models of the processes support optimization by revealing bottlenecks and validating structural efficiency. Therefore, the digital twin of an organization based on the digital copy of a physical asset allows real-time data of the current process to be assessed and collected, information of the interaction with the environment to be derived and information traces captured.

5.4 Method for managing data-driven business processes: A guideline

This section discusses the methodology for developing business process management. This research provides a guideline for realizing I4.0-driven business processes by utilizing technological developments. Based on the previously presented

detailed analysis, this section outlines how and at which stage of a project emerging technologies and data-driven decision support tools can be utilized to endure process efficiency and rebound business agility.

Following the BPM life cycle (Figure 5.2) through innovative I4.0 projects is suggested, which require business processes to be redesigned through iterative, knowledge- and data-centred process analysis, following the design science research paradigm. BPM is a comprehensive system to transform business operations through modeling, execution and evaluation. Its life cycle model provides a transparent reference 'step by step' model to transform processes successfully. To ensure business agility, competitiveness and smart growth, organizations must accomplish a transparent, interconnected, real-time and virtual data-based workflow management. These features can be derived by utilizing the potential of, for example, process mining, IoT, BPMN models, ontologies and semantic models, robotic process automation, digital twins and simulation models. These technological alignments are categorized into the phases of the BPM life cycle outlined in Table 5.1. Furthermore, integrating business analytical standards into the BPM life cycle, such as CRISP-DM/ML is suggested. Table 5.2 defines the connectivity features between the models. Businesses' vast amount of heterogeneous data must be managed to continuously recognize, analyze, improve, and implement changes within business processes. Since data mining and machine learning projects closely related to AI tend to increase in an industrial concept, supporting cross-industry standards for machine learning and data mining are essential. Especially in manufacturing, which is of the most promising area to successfully apply digital twin for maintenance and operation monitoring and optimization purposes [275].

Table 5.3 presents a higher level of integrability of the concept mentioned above related to how phases of the BPM life cycle, as well as data-driven standards and ontologies, are related at different levels of the organizational hierarchy (business, process, implementation). The BPM life cycle and CRISP-ML model is broken down according to organizational hierarchy levels. This point of view supports the comprehensive understanding of which stage of the project belongs to which level of organizational operation.

TABLE 5.3: The intertwining of the BPM life cycle and standard models at the levels of organizational hierarchy (Source: Ref. [6])

Hierarchical levels	**Definition**	**BPM life cycle phasis**	**CRISP-DM/ML phases**	**Supporting standards**
Business	Used by executives and senior business managers to organize their overall understanding, evaluation, and management of a business's performance.	Process identification, Process discovery	Business understanding	BPMN, UML AD, B2MML, OPC UA: IEC 62541, BPDM, OI40, CDD
		Process analysis	Data understanding	
		Process monitoring and controlling	Monitoring and maintenance	
Process	Used by managers, employees, business analysts, and human performance analysts to change how processes work.	Process analysis	Data preparation, Evaluation	BPMN, ISO/PRF TR 24464, ALPS, ADACOR, BPQL, OPC UA: IEC 62541, BPML, BPDM, CDD, IEEE 1872-2015 standard
		Process redesign	Modeling	
		Process monitoring and controlling	Monitoring and maintenance	
Implementation	Technology used to implement processes according a context defined in upper levels. It can also be used to to develop job descriptions or hire new collaborators.	Process implementation	Deployment	AutomationML, FDI, EDDL, AASX, WSBPEL, EDI, ORArch
		Process monitoring and controlling	Monitoring and maintenance	

5.5 Results and discussion

This section presents a case study in which a BPM life cycle and I4.0-driven tools are applied to redesign a production line of CNC machines. The case study is of a Hungarian assembly and engineering company oriented in Industry 4.0 technology applications. The project aims to redesign the production line of CNC machines into a fully automated 'smart' factory unit and replace the current product tracking system with a flexible manufacturing execution system (MES). This case of redesigning the business process should significantly build on data-driven and I4.0-induced developments, tools and methods as the design of the planned automated factory unit and integration of the manufacturing execution system into the current phases require the detailed analysis and redesign of the business processes.

5.5.1 Redesign of a CNC production line

In this section, the details of the guideline proposed in Section 5.4 are presented.

The purpose of this demonstration is twofold: 1) the development project through the phases of the BPM life cycle and its decision support tools, then 2) to create the BPMN-based simulation model of the 'to-be' model to validate its structure as well as examine and analyze its processes. Simulation of the process is used as a tool to validate and continuously monitor the efficient operation of the tasks as well as gather real-time information traces and data sets. Figure 5.4 shows the workflow of redesigning business processes while considering business analytic (CRISP-DM/ML) aspects at a Hungarian assembly company. The workflow follows the data-based BPM life cycle steps and indicates tools and methods applied at each step.

The current processes were identified through observations, in-depth interviews with employees, organizational databases and enabled to gain a comprehensive understanding of business background and objectives. Processes were discovered by analyzing log files, namely registries of events, processes, messages and communications, that were utilized to recreate the proper structure and attributes of processes. As soon as we see how the company works, improvement ideas undoubtedly will show up. BPMN modeling helps to understand the answers to the questions like: How do they work? Why do they work based on this strategy?

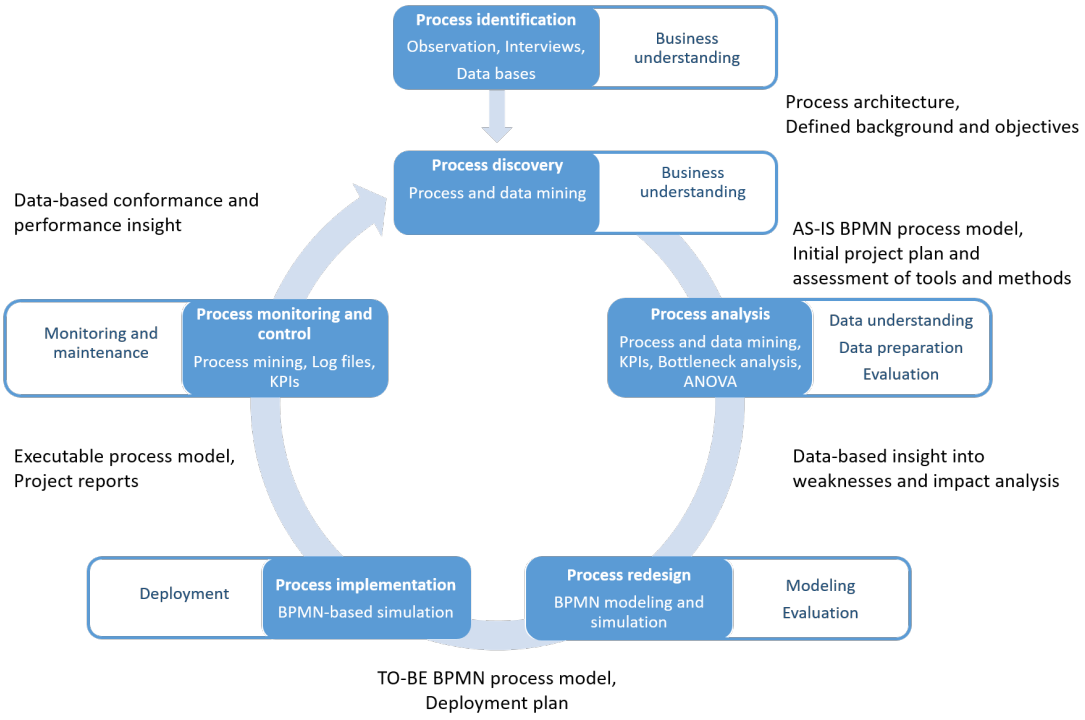


FIGURE 5.4: Workflow of redesigning business processes at a Hungarian assembly company (Source: Ref. [6])

How can it be improved?. In order to graphically reconstruct the 'as-is' state, a BPMN model of business processes is built to ensure transparency and support the identification and discovery phases and bottlenecks. The data-based analysis of the current process model was carried out by process- and data mining, analysis of KPIs and bottleneck, and ANOVA analysis to reveal weaknesses and possible development areas. Examination of the extracted data and log files enabled to define bottlenecks to be identified. The redesign of business processes was carried out using BPMN modeling for the desired automated manufacturing process. A BPMN model of the 'to-be' improved the current processes, and the automated factory unit ensured its transparency and ability to be simulated (deployed). The improvements based on the KPIs can be evaluated similarly to Ref. [276]. As the application study is based on a continuous development project at the Hungarian assembly company, there were no opportunities to implement the 'to-be' model in a traditional (physical) way. Therefore, a simulation model was developed from one hand to previously assess how the changes would affect the outcome and other processes and reveal further potential bottlenecks. The simulation of the business process model includes information about time periods, executors and resources to analyze processes and reveal possible bottlenecks. A simulation technique is

used to find the potential flaws in the current processes and to realize/optimize the design of the process improvements/experiments [277]. The developed simulation model enables the process structure and allocations to be validated, thereby ensuring the implementation phase is efficient.

The simulation environment is implemented in a Python environment with the package called Casymda [278]. Casymda enables SimPy [279] discrete simulation models to be created with the help of BPMN designed using Camunda Modeler [280]. Camunda Modeler helps to ease the creation of simulation models containing more complex processes. By using a defined subset of available BPMN elements combined with naming conventions, model graphs can be created to derive corresponding Python modules from base templates. The model graph is used to define the instantiation of model objects and predecessor/successor relationships between these objects. The initialization of work-in-progress (WIP) in the simulation model is realized using entry points of the model elements. It accounts for seized resources and the processing time that has already passed following the start of the simulation by comparing an entity's entry timestamp to the starting time of the simulation. The entities follow their normal processing flow [281].

The constant monitoring and control function is implemented by detecting information traces through process mining. In order to evaluate the results, indicators were defined concerning, e.g. time, cost, performance, utilization. Four types of performance indicators were used: the mean waiting time of the entities before being processed by the resources, the values of stock waiting to be processed, capacity, and utilization of the resources.

It should be noted that given the demands of continuous improvement, this workflow should return to the first stage.

5.5.1.1 Details of BPMN model development

A simplified BPMN model of the processes is shown in Figure 5.5. The production processes consists of four segments, which are described below:

- *Technologist work*: One technologist operator makes decisions about the processes to be performed by the ordered product. This operator's tasks are presented in Figure 5.5 from $P1$ to $P11$ and from $P15$ to $P19$. Typically, one technologist operator works during each shift.

- *Programming*: There are programmers who write CAM programs for CNC milling. Their processes are described in Figure 5.5 from $P20$ to $P23$. Usually, five programmers work during each shift.

- *Cutting plant*: In the cutting plant, the raw materials are cut to the desired dimensions for CNC milling. These processes are described in Figure 5.5 from $P12$ to $P14$, where the walking processes are also indicated. On average, two operators work during each shift.

- *Milling plant*: CNC milling operators handle the CNC machines. Their processes are described in Figure 5.5 from $P24$ to $P42$ besides the walking processes. Typically, six operators work during each shift and are individually assigned to work on one of the eight CNC machines available.

An overview of the processes is presented in Figure 5.5, where the detailed structure of the cutting plant is also presented. The technologist starts the process, who decides about the appropriate steps to perform to get the desired product. Then the cutting machine operators prepare the raw materials for CNC milling. Subsequently, as the exact dimensions of the raw material to be cut are known, the programmer or the CNC operators write the CAM programs to be used for milling. Currently, 30% of the CAM programs are made by CNC operators at the manufacturing plant. As soon as the CAM program is available for production, the CNC operators can commence their work.

As the processes concerning the third stage of the workflow have been thought through, many improvements can be recognized. BPMN-modeling, so the understanding of the 'as-is' state in collaboration with the company's process engineers help a lot in figuring out the possibilities for process improvement. These activities help to understand the reasons behind their working and operating strategy, and they help to identify the bottlenecks. On the other hand, BPMN-based simulators can provide a systematic solution to identify the bottlenecks of the system [277]. In our case, the following improvements are investigated by evaluating different KPIs:

- *First case*: It is believe the CNC operators should not spend their valuable time writing CAM programs since this would decrease the utilization of the CNC machines. Programmers should write all the CAM programs.

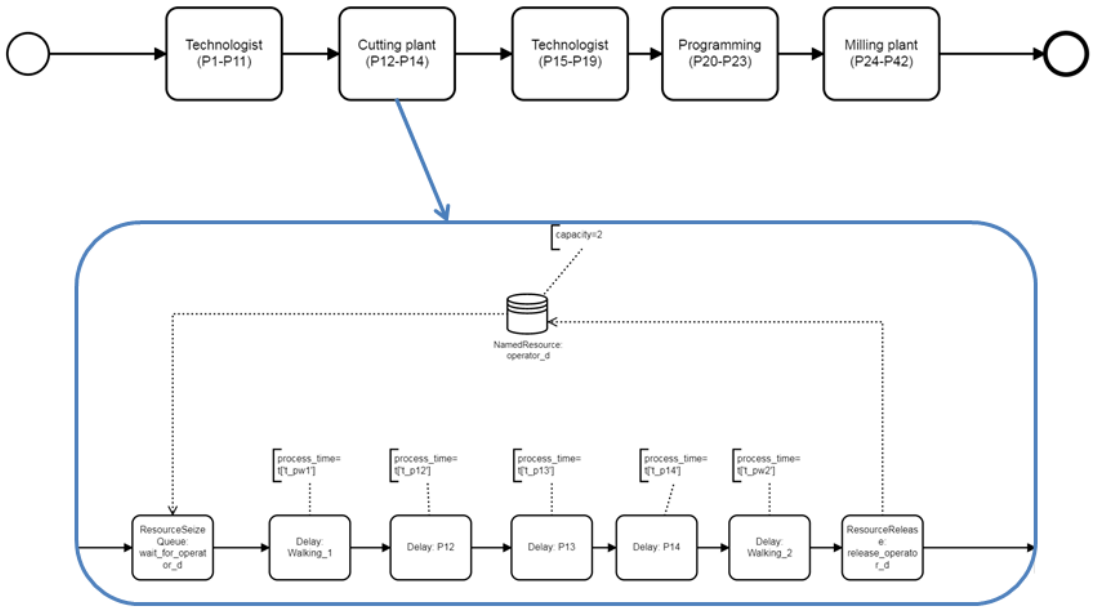


FIGURE 5.5: Process overview (Source: Ref. [6])

- *Second case*: While the CNC machine is being operated, the CNC operators can handle other production tasks using other available CNC machines instead of being idle.
- *Third case*: The third possibility is to decrease the non-value added activities of the operators, so AGVs (automatic guided vehicles) can transport raw materials and products instead of the operators. Furthermore, the virtualization of the drawings could be considered, so sheets of paper do not need to be handled.

5.5.1.2 Exploratory data analysis and prediction model development

An experimental test environment has been installed in the CNC milling plant, which the process engineers consider as a "quasi" smart unit. It practically means a process improved unit, where the CNC milling operators do not develop CAM programs, and every necessary raw material and tool is immediately available.

To show the difference between the systematic and unsystematic operation, the utilization of the CNC milling machine increased by 30% in the test environment. It leads to the fact that there is a huge potential in the performance improvement at the investigated company, making the goal much more attractive.

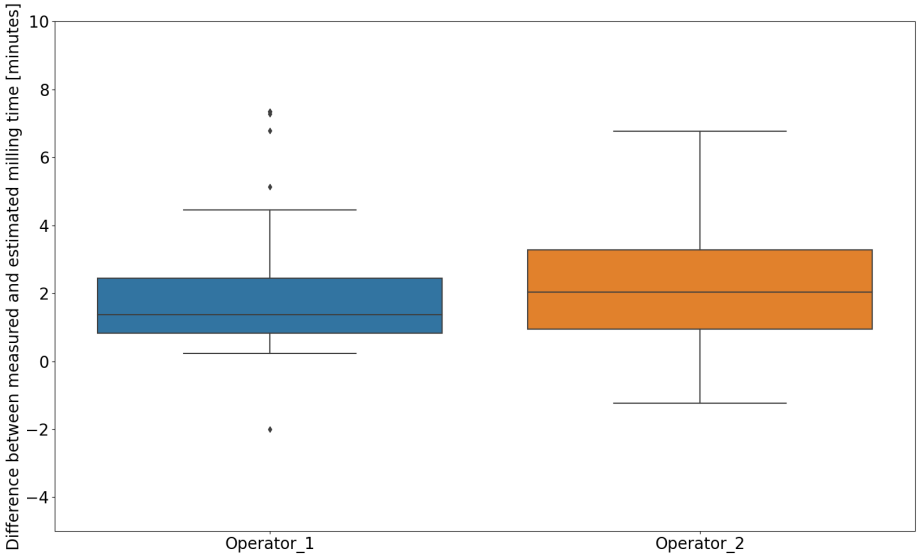


FIGURE 5.6: The box-plots of the difference times between the measured and estimated milling times by the operators (Source: Ref. [6])

However, this process improvement on the whole plant is not easy since it is necessary to explore all the variables affecting the utility and performance. It is necessary to predict how these variables affect the performance indicators. Moreover, the best possible schedule can be reached only with accurate models. For this purpose, the data provided from the test environment was investigated, and presented how the real CNC milling times can be predicted based on the estimated CNC milling times found in CAM files.

An ANOVA test was performed to justify that the difference between the measured and estimated CNC milling times is independent of the operator or not. The null hypothesis is that all difference means are equal, which is rejected since the F-score is 118.6 while the critical value is 3.7. It means that the differences are not independent of the operator, which result is supported too with the box-plots shown in Figure 5.6. It is worth noticing that the difference is positive, so the measured milling times are higher than the estimated times.

In the following, it has been investigated how the difference between the measured and estimated milling times varies with the estimated milling times and with the number of the required tools for milling, as it is presented in Figure 5.7. As can be seen, the residuals increase both with the estimated milling times and the number

of required tools. Hence both variables are considered in the prediction. Since the residuals are not independent of the operators, two linear models were developed to predict milling times. However, the coefficient of the variable presenting the number of tools in case of *Operator_1* is 0.01 and its p-value is 0.8 (> 0.05), while in case of *Operator_2* the coefficient is 0.3 and its p-value is 0.02 (< 0.05). It means that the number of required tools affected only the milling time in the case of *Operator_2*.

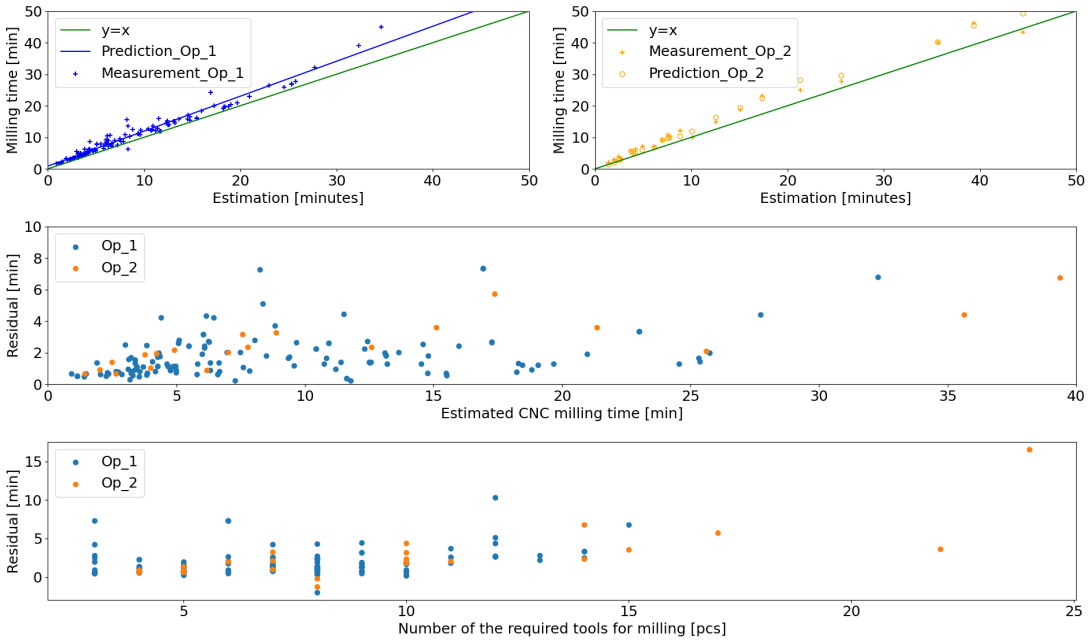


FIGURE 5.7: Analysis and prediction of milling times (Source: Ref. [6])

An applicable result for the company is that the measured milling times are not independent of the number of the required tools. It comes from the fact that the tool shelf does not have enough slots to store all the necessary tools, and changing the tools is an additional non-value activity. Therefore, the company will change the shelf to a bigger one and eliminating this unnecessary activity.

On the other hand, using the developed prediction models, the root mean squared error (RMSE) decreased from 2.5 minutes to 1.4 minutes in the case of *Operator_1*, and it decreased from 4.5 minutes to 1.9 minutes in the case of *Operator_2*, so the activity times of the milling can be predicted more accurately.

A small part of model development is presented, which process accompanies the whole business process improvement. CRISP-ML supports and helps to perform the process development more accurately and systematically.

5.5.1.3 Details of the simulation and process mining

Following the implementation of the suggested improvements, the 'to-be' BPMN model is built. The built BPMN models can be used to simulate the different variations concerning the operations using Casymda and the operation structures evaluated by calculating the relevant KPIs concerning the fourth stage of the workflow.

The BPMN process model was developed in Camunda Modeler based on company consultations, process-engineering discussions, observations, and the analysis of available operational data and logs; from the more detailed internal model, a representative sub-model was selected for demonstrative simulation purposes. The simulation was implemented in Python using Casymda as a discrete-event model, with incoming workpieces as entities, a maximum of 50 entities, an inter-arrival time of 10 time units, a 7.5-hour simulation horizon, and the main resources defined as operator = 7, programmer = 6, technologist = 1 and cutting = 2. The model was checked through expert-based validation of the BPMN logic, KPI-based simulation evaluation, and process-mining-based inspection of the generated event logs.

The first scenario is simulated by directing all the entities directly to the programmers. The second case is simulated by queuing the appropriate resources in the proper order. In the simulation, the entities are first queue CNC machine as a resource. Then, if available, an operator is queued to perform the necessary processes. Then if CNC milling is the process to be performed ($P36$), the operator is released to undertake other processes. If the milling process is conducted, an operator is required to continue the manufacturing process. The third case is simulated by adjusting the walking time to zero minutes. In this case, it is assumed that an AGV is always available to transport materials, and the transportation processes do not hinder other processes.

Process mining techniques can be applied to validate and verify the developed process model and simulator by analyzing a log file generated with the developed simulator. Process mining is a powerful tool to verify that the obtained results and analysis are consistent with the present 'as-is' and the desired 'to-be' systems. The log file generated from the simulation holds information about the events, processes and communication messages that enable the simulated process to be reconstructed and its operations investigated.

Concerning the sixth stage, the investigated KPIs in each case was presented, and it can be seen that all the suggestions improve the performance of the manufacturing unit.

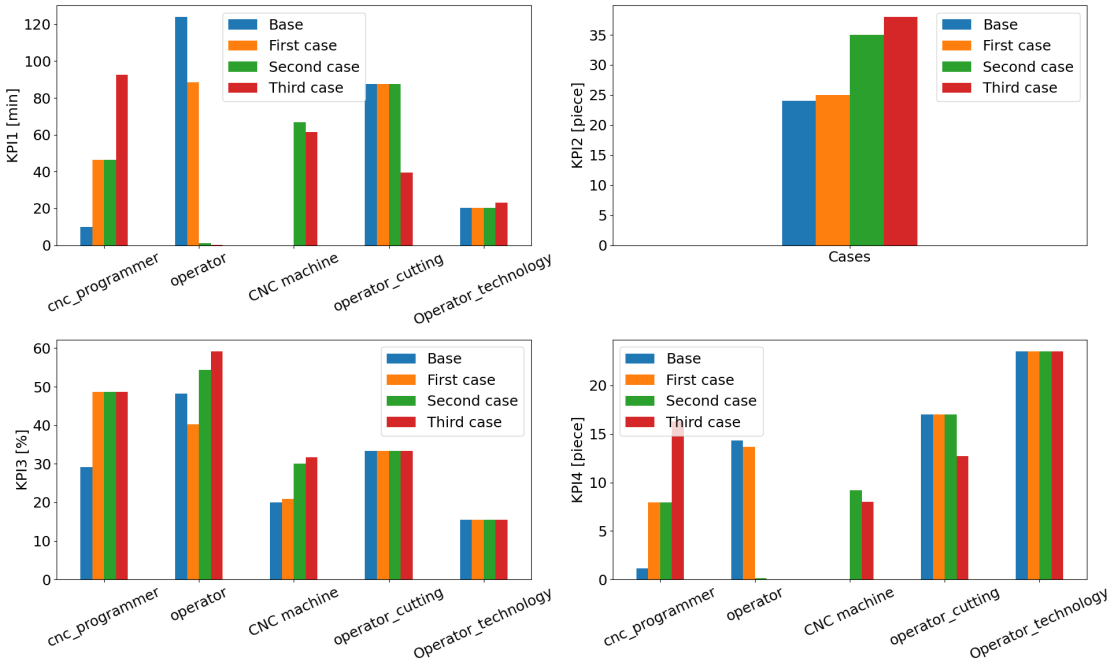


FIGURE 5.8: KPIs of the different cases ($KPI1$: Average mean time, $KPI2$: produced quantity, $KPI3$: Resource utilization, $KPI4$: Stock)(Source: Ref. [6])

By evaluating step-by-step the KPIs, we can gain valuable information about the processes and their structures. In the first case, all CAM programs are written by the CAM programmers resulting in a slight increase in $KPI2$, therefore, an increase in the quantity produced per shift. As a consequence, the average waiting time of entities ($KPI1$) to be processed by CAM programmers increased, so the resource utilization ($KPI3$) and the stock quantity ($KPI4$). The average waiting time is about 45 minutes, the average stock is eight pieces, and the degree of utilization per shift is 50%. In the second case, the milling operators can handle more CNC machines, which would suggest a significant increase in capacity. The quantity produced per shift rose from 25 to 35 to be exact. As shown from $KPI1$, the operators are not subjected to significant waiting times, unlike the CNC machines, which means that the number of CNC machines is the relevant constraint. In the third case, the materials are transported by an AGV robot and all information is visualized. It increases the production capacity slightly and reduces the waste time so the cutting operators can finish their tasks earlier, as seen from $KPI4$.

However, this leads to an incremental change in $KPI1$ and $KPI4$ at CAM programmers. Following the suggested process improvements, we can increase the production capacity, which our simulation has demonstrated.

5.5.2 Evaluation of the results

The evaluation of the simulation results is structured according to the six stages of the workflow shown in Figure 5.4.

1. **Process identification**: The combination of the observation method, in-depth interviews and the analysis of databases (product tracking system and CAM files) allowed a common understanding of the current processes as well as the structure and operation of the automated factory unit to be gained.

2. **Process discovery**: The BPMN graphical notion of the 'as-is' model brings about a transparent visualization and logical structure to the concept.

3. **Process analysis**: The extracted data is analysed by data and process mining tools. The impact of operator on the CNC milling times was analysed by ANOVA. The model was optimized according to the defined KPIs (e.g. time, cost, utilization).

4. **Process redesign**: The BPMN model of the 'to-be' model is built to ensure transparency. The process model supported the specification of the MES and defined which characteristics we aimed to measure.

5. **Process implementation**: The BPMN-based simulation model of the 'to-be' stage is built.The simulation model is based on BPMN, and parameters concerning time, costs, and resources can be added. The simulation reveals logical and structural efficiency and provides information about the utilization and operators of business processes. Furthermore, it allows possible modifications to be tested before putting them into practice. The simulation model revealed information about the steps and supported the identification of which variables should be measured.

6. **Process monitoring and control**: The results are evaluated by comparing KPIs and revising the model. Further and continuous innovations and the revision of the processes are essential.

This project phase covers the six stages of the BPM life cycle: identification, determination, analysis, redesign, implementation (simulation) and the constant monitoring of processes. As a result, an outline of the desired business process is determined. The simulation model enabled the processes to be brought to life by adding time, costs, and resources parameters to the model. Later in this project, these attributes will be added to the concept, along with the analysis of log files used to validate its efficiency. Thereby, the evaluation of current processes is possible, and estimations can be made in advance. The model must be capable of handling and cooperating with information systems; moreover, data exchange based on standards must be considered. The integration and implementation of the concept is a complex task that requires further examination and constant evaluation.

The proposed methodology guides managing business processes in the age of Industry 4.0. The application of the methodology requires the capability to adapt to I4.0 technologies and organizational changes. To implement the I4.0 concept, companies must address significant challenges as well as develop internal and external capabilities, and processes [282]. Organizations must be aware of their I4.0 maturity level in order to facilitate the understanding and evaluate actual business state, process architectures ('as-is' model), as well as accurately determine development strategies [225].

Maturity models reveal key focus areas as 'Strategy', 'Operation', 'Products', 'People', 'Technology' and 'Data and information'. An organizational strategy is what propels this transformation process towards the concept of I4.0. Operation refers to vertical and horizontal value-chain integration, which cannot be managed without an advanced technological background to share and exchange information. The result is a network of cross-enterprise planning and control of the entire product life cycle. Moreover, the integration of the production system offers the potentials to enhance productivity, quality and flexibility [60]. However, people cannot be neglected as they are the key drivers of knowledge. Continuous training of the workforce is needed to meet new skill-set requirements. Technological adaptations and changes across the organization demand complex and cross-functional skills and abilities such as logical and mathematical reasoning, flexibility and creativity, problem sensitivity, active learning critical thinking, coordination and negotiation skills, digital and analytical skills, technical and management skills, systems thinking and complex problem-solving skills [283].

These skill-sets enables the workforce to have high flexibility and faster adaptation to the continuously changing business environment, critically analyze data- and knowledge-driven processes and integrate new technological developments, tools and methods.

The continuous development and optimization procedures require a wide range of knowledge and methods to be applied to gain a comprehensive insight into the operation of business processes. The data-driven redesign of business processes is resource-intensive due to high complexity data and expects an integrated data management system to ensure overall data availability within the organization. Although process mining is an efficient tool for discovering business processes to derive BPMN models, some requirements need to be addressed. Such as data reliability, correctness and completeness, as well as event logs should be recorded in a way to ensure privacy and security [230].

Organizations that strive to succeed in the I4.0 environment can utilize this concept to gain a shared understanding of the interrelation between BPM, business data analytics and data-driven technologies. Furthermore, researchers in the field may deem the development of the business process management life cycle via I4.0-driven and data-based decision support tools to be suitable.

5.6 Conclusion

Research and innovation projects are gaining increasing attention concerning the organizational implementation of the Industry 4.0 concept and digitization perspective. Organizations must follow and predict industrial trends and integrate new technologies and methods into their BPM life cycle to keep up with competitors. The number of trends in AI- and ML-based decision support tools is increasing [284], which underlines the necessity to integrate data-based business analysis techniques and standards (CRISP-ML) into the BPM life cycle.

The primary objective of this research was to provide a guideline for continuously developing business process management through iterative, knowledge- and data-based analysis by utilizing I4.0 applications, tools and methods. According to recent trends, organizations must innovate and optimize their business processes to maintain their competitive advantage in the market and rebound business agility. Real-time capability, transparency, interoperability and interconnectivity have become the primary features of businesses, which can be implemented through data-driven workflow management. This research highlights the potential to integrate business process management approaches, business and data analytics, and supporting tools and methods. The integration of decision support tools such as process mining, simulation models, digital twins and data analytics systems and related standards are suggested as a core component to support the phases of the BPM life cycle. These phases are: identifying, discovering, analyzing, redesigning, implementing, and monitoring and controlling.

Through the case study of a Hungarian assembly and engineering company, the proposed concept was demonstrated. The presented project aims to redesign current processes to integrate a manufacturing execution system (MES) and build a fully autonomous factory unit that enables the realization of individual manufacturing tasks from control to physical operations. The BPMN-based simulation model of the 'to-be' processes was made to evaluate the structural efficiency and track information traces. In this case, the resources and time periods of the steps were added to the model to analyze both the number of tasks that need to be done and those that are derived within a given time period. Information stored in the MES enabled data to be identified, discovered and analyzed in real-time. Furthermore, to continuously monitor and develop the operation of the autonomous factory unit, optimization algorithms must be applied.

This research highlighted that the emerging technologies connected to the BPM life cycle and the CRISP-ML concept serve the same goal: integrating I4.0 developments and business analytics into the business process management phases. Innovative projects such as creating an automated factory unit cannot be realized without AI and ML technologies and decision support tools, including modeling, augmented data management and analytical techniques. In the future, AI and ML applications will gain greater importance in addition to analytical techniques and decision intelligence, including modeling. These trends and techniques play a significant role in predicting and optimizing business processes and efficiently realizing innovative projects. Consequently, organizational business processes in the age of I4.0 must be supported with novel tools to adapt to industry trends and rebound business agility.

Besides supporting data-driven business process optimization, the proposed BPM guideline also contributes to sustainable manufacturing by operationalizing sustainability at the process level. Throughout the BPM life cycle, Industry 4.0 technologies enable the continuous measurement and improvement of resource utilization, production efficiency, material consumption, energy demand, and human-centred working conditions. However, these sustainability co-benefits should not be regarded as automatic outcomes of digital transformation but as measurable improvements that depend on appropriate organizational objectives, implementation practices, and performance indicators.

This chapter provides the process-level pillar of the thesis. By proposing and demonstrating an integrated BPM–CRISP-ML-based guideline for data-driven, Industry 4.0/5.0-oriented process development, it directly substantiates Thesis IV. In doing so, it builds on the global, regional and organisational insights of the previous chapters and translates them into actionable methods for designing, implementing and continuously improving digitally enabled production processes.

From a cross-level perspective, the process-level findings also reveal several alignment and generalizability gaps, as well as implications for bottom-up feedback to the organizational, regional, and global levels. The process-level framework demonstrates how data-driven BPM, manufacturing information systems, process modelling, simulation, and analytical methods can support the redesign and continuous improvement of operational workflows. However, the process-level analysis alone cannot determine whether the selected improvement objectives reflect the

most relevant organizational sustainability priorities, whether the required technologies are supported by the surrounding regional ecosystem, or whether the resulting local performance changes contribute meaningfully to broader SDG and ESG-oriented objectives.

This creates an alignment gap between local optimization and higher-level transformation goals. Improvements in cycle time, throughput, resource utilization, inventory, or information availability may generate important operational benefits, but they should not automatically be interpreted as comprehensive sustainability improvements. Their environmental, social, governance, resilience, and human-centric implications must be evaluated through organization-specific objectives and indicator systems. The organizational framework in Chapter 4 therefore provides the strategic requirement structure within which process-level KPIs should be selected and interpreted.

A second gap concerns external enabling conditions and scalability. The successful application of data-driven BPM depends on skills, digital infrastructure, institutional support, investment capacity, and technology availability, which are partly determined by the regional readiness conditions analysed in Chapter 3. A process solution demonstrated in one company cannot be assumed to be equally feasible or effective in regions or organizations with different capability profiles.

A third gap relates to generalizability. The CNC production-line application demonstrates the feasibility of the proposed methodological integration in a specific industrial context, but the numerical results and the relative benefits of the redesign alternatives are case-dependent. Further applications across sectors, organizational sizes, process types, and technological environments are required to assess external validity and to refine the guideline.

At the same time, process-level data provide the most concrete source of bottom-up feedback in the multi-level framework. Aggregated operational evidence on resource use, productivity, quality, safety, human–technology interaction, and environmental performance can support the revision of organizational priorities, inform regional capability-development programmes, and contribute to broader sustainability monitoring. Establishing standardized mechanisms for this upward data transfer remains an important area for future research.

Chapter 6

Summary and thesis findings

This chapter summarizes the scientific results of the thesis and formulates the thesis statements. Beyond summarizing the results of the previous chapters, the chapter also explains how the four research blocks form a coherent multi-level framework for sustainability-oriented Industry 4.0 and 5.0 transformation.

Accordingly, this chapter is structured as follows. Section 6.1 presents the multi-level synthesis of the thesis, including the research objectives, research question groups, chapter-level contributions, methodological connections and transfer logic among the four levels. Section 6.2 formulates the thesis statements.

6.1 Multi-level synthesis of the research objectives, questions and results

The overall objective of the thesis was to develop data- and systems-science-based frameworks that support the analysis, planning, prioritization and implementation of sustainable Industry 4.0 and 5.0 transformation. The motivation of the research is that the green and digital transition unfolds across multiple decision levels. Global sustainability narratives and SDG-related challenges shape the external context of transformation; regional capabilities determine whether Industry 4.0 developments can be introduced and scaled; organizations translate sustainability expectations into Industry 5.0 solution portfolios; and the actual implementation of digital transformation takes place at the process level.

The thesis is organized around four research question groups. Each group corresponds to one analytical level, one main methodological framework, one dissertation chapter and one thesis statement as shown in Table 6.1.

TABLE 6.1: Alignment of analytical levels, research question groups, objectives, chapters and thesis statements

Levels	Research question group	Main objective	Chapter	Thesis
Global level	How can sustainability-related issues be identified and analyzed through world news and network analysis?	To develop a news-based monitoring framework for identifying SDG-related topics, country profiles, tone and co-occurrence structures.	Chapter 2	Thesis I.
Regional level	How can the regional development conditions of Industry 4.0 solutions be measured?	To develop an open-data-based regional Industry 4.0+ readiness model and ranking methodology.	Chapter 3	Thesis II.
Organizational level	How can sustainability requirements be connected to Industry 5.0 solution families?	To develop a QFD- and network-analysis-based decision-support framework for company- and industry-specific prioritization.	Chapter 4	Thesis III
Process level	How can Industry 4.0 tools be integrated into business process management?	To develop a data-driven BPM and CRISP-ML(Q)-based guideline for process redesign and continuous improvement.	Chapter 5	Thesis IV.

The four levels represent different decision tasks, but they follow a common systems-science logic. At each level, heterogeneous information is transformed into structured and interpretable decision-support models. At the global level, this information consists of news, SDG-related taxonomies and country-level co-occurrences. At the regional level, it consists of open indicators describing skills, innovation, investments, technology and labour-market conditions. At the organizational level, it consists of sustainability requirements, reporting topics and Industry 5.0 solution families. At the process level, it consists of process models, manufacturing data, simulation results and performance indicators.

The analytical levels are connected not because the output of one model automatically becomes a direct input to the next, but because each level resolves a decision gap left open by the preceding level. The global analysis identifies sustainability-related attention patterns but does not measure territorial implementation capacity; the regional model evaluates enabling conditions but does not select organization-specific development priorities; the organizational framework prioritizes Industry 5.0 solutions but does not implement them in operational workflows; and the process-level framework demonstrates implementation but requires higher-level objectives for interpreting and scaling its results. The multi-level contribution of the thesis therefore lies in the complementary closure of these decision gaps and in the establishment of top-down orientation and bottom-up feedback pathways across the four analytical levels.

While Table 6.1 summarizes the vertical structure of the dissertation, Table 6.2 focuses on the interfaces between the analytical levels. These interfaces are important because Industry 4.0 and 5.0 transformation rarely progresses in a linear way. Global SDG and ESG expectations influence regional policies, organizational strategies and process-level KPIs, but at the same time operational evidence, organizational disclosures and regional capabilities also feed back into broader policy and sustainability narratives. Therefore, Table 6.2 presents each pair of levels through three interpretive dimensions: the top-down question, the bottom-up question and the likely conflict that may emerge between the two perspectives. The last column then explains how the methodological toolkit of the thesis helps to bridge these tensions.

This multi-level alignment of Industry 5.0 ans sustainability questions and the tools utilized in the thesis are mapped in Table 6.2.

TABLE 6.2: Multi-level alignment of Industry 5.0 and sustainability questions in the thesis toolkit

Pair of levels	**Top-down question**	**Bottom-up question**	**Likely conflict**	**How the thesis toolkit helps**
Global - Regional	Which SDG/Industry 5.0 issues should guide regional policy and funding?	Which regional capabilities and bottlenecks should be elevated to European/global attention?	Global priorities may be too general; regions differ in skills, innovation systems and industrial structures.	GDELT maps attention and issue salience; I4.0+ index translates priorities into NUTS-2 capability diagnostics.
Global - Organizational	Which global SDG/ESG expectations create legitimacy and reporting pressure for firms?	Which corporate practices and disclosures can reshape global norms and narratives?	Organizations may face reporting pressure without clear technology-selection logic.	QFD links SDG/GRI requirements to Industry 5.0 solution families; network analysis highlights central requirements and solution bundles.
Global - Process	Which global sustainability objectives must become operational KPIs such as energy, waste, safety and traceability?	Which operational results can contribute to global best-practice narratives?	SDG targets are high-level, while process data are granular and local.	BPM and CRISP-ML(Q) decompose high-level goals into measurable process indicators and data pipelines.
Regional - Organizational	Which regional readiness profile enables or constrains firm-level Industry 5.0 adoption?	Which organizational investments create regional spillovers in skills, suppliers and innovation?	A firm may need capabilities that the region cannot yet supply.	I4.0+ index identifies human-capital, innovation, investment and technology constraints; QFD helps firms select portfolios that are realistic under those constraints.
Regional - Process	Which regional infrastructure and training systems are needed for process digitalization?	Which process innovations can diffuse through suppliers, training centers and regional policy?	Process innovations may remain isolated pilots if regional diffusion channels are weak.	I4.0+ index diagnoses diffusion potential; BPM case demonstrates transferable operational practices.
Organizational - Process	Which strategic I5.0 solution portfolio should be implemented in workflows?	Which process KPIs reveal whether the strategy actually works?	Strategic ESG language can remain disconnected from shop-floor routines; process improvementcan optimize efficiency without sustainability KPIs.	QFD translates requirements into solution families; BPM/CRISP-ML(Q) translates solution families into process models, data flows and KPIs.

The main message of Table 6.2 is that the levels are connected by translation problems. Global sustainability objectives must be translated into regional policy priorities, organizational requirements and measurable process indicators. At the same time, local evidence must be aggregated and interpreted in a way that can inform organizational learning, regional development and broader sustainability debates. The table also shows that each interface involves a characteristic risk: global priorities may remain too general for regional implementation; firms may face ESG reporting pressure without a clear technology-selection logic; and process improvement may optimize efficiency without explicitly addressing sustainability and human-centricity. The thesis toolkit addresses these risks by combining GDELT-based monitoring, the I4.0+ readiness index, QFD-based requirement translation, network analysis and BPM/CRISP-ML(Q)-based process development.

The coherence of the dissertation is not only ensured by the thematic connection between the four levels, but also by the transferability of the applied analytical logics. Several methods used in the thesis can be interpreted as reusable systems-science tools. Network analysis, ranking, requirement translation, lifecycle thinking and simulation appear at different levels with different units of analysis, but they serve similar decision-support functions. Table 6.3 therefore summarizes how these methodological logics are applied in the thesis and how they could be extended across the other analytical levels.

Table 6.3: Method-transfer matrix, potential utilization of the tools at different levels

Method or analytical logic	**Global use**	**Regional use**	**Organizational use**	**Process use**	**Transferability claim**
Network analysis	Country-SDG and country-country co-occurrence networks; hub and community detection in sustainability discourse.	Potential extension: inter-regional collaboration or knowledge-flow networks based on projects, patents or mobility.	Bipartite SDG-GRI-I5.0 networks; centrality and communities identify solution bundles.	Potential extension: process networks, resource networks, machine-task dependencies.	The same graph logic moves from discourse structures to capability systems, requirement systems and workflow systems.
Composite indicators and ranking	Potential extension: SDG attention/tone indices by country or region.	PROMETHEE/PCA/SRD-based I4.0+ readiness ranking.	Weighted QFD scores and I5.0 solution importance rankings.	KPI dashboards and scenario ranking for process redesign alternatives.	Ranking is a recurring decision-support operation, but the unit changes from countries/regions to solutions and process alternatives.
QFD / requirement translation	Potential extension: mapping global SDG narratives to policy objectives.	Potential extension: mapping regional bottlenecks to funding and training programs.	Core application: mapping SDG/GRI requirements to I5.0 solution families.	Potential extension: mapping organizational requirements to process parameters, sensors, tasks and KPIs.	QFD becomes the mechanism for top-down decomposition of goals into design characteristics.
BPM and lifecycle thinking	Potential extension: monitoring policy cycles and public attention cycles.	Regional roadmaps can be treated as policy-process lifecycles.	Organizational strategy and reporting can follow plan-measure-implement-report cycles.	Core application: BPM lifecycle integrated with CRISP-ML(Q) for process redesign.	Lifecycle thinking aligns planning, execution, monitoring and feedback across levels.
Simulation and scenario analysis	Potential extension: media-attention scenariosor policy shock scenarios.	Regional development scenarios based on readiness bottlenecks.	Portfolio scenarios for I5.0 solution investment.	Core application: BPMN simulation of CNC redesign alternatives.	Simulation supports "safe-to-fail" experimentation before expensive implementation.

Table 6.3 demonstrates that the methodological contribution of the thesis is not limited to the individual models developed in the separate chapters. Rather, the contribution lies in the combination of these models into a transferable analytical toolkit. Network analysis is used to reveal structures and communities; composite indicators and ranking methods support prioritization; QFD translates high-level requirements into design characteristics; BPM and lifecycle thinking connect planning with implementation and feedback; and simulation enables the testing of alternative development scenarios before implementation. These methods jointly support the movement from observation to decision and from decision to implementation.

Therefore, the thesis contributes to sustainability-oriented Industry 4.0 and 5.0 transformation in two ways. First, it provides level-specific frameworks for global monitoring, regional readiness assessment, organizational prioritization and process-level implementation. Second, it shows how these frameworks can be connected through common systems-science principles and data-driven decision logic. This synthesis provides the basis for the thesis statements formulated in the following section.

6.2 Thesis statements

Within this overall framework, the original contribution of the thesis is formed in four theses, each corresponding to one analytical level and underpinned by publications. Thesis statements are presented below. The Hungarian thesis statements can be found in Appendix G.

Thesis I. I demonstrated that the developed news- and network-analysis-based toolkit is suitable for the global-level identification and analysis of sustainability-related problems [1].

I.I I demonstrated that by linking world news with taxonomic categories associated with the Sustainable Development Goals, a data-driven monitoring system can be developed that complements traditional indicator-based SDG assessments. The method uses the GDELT database and the World Bank Topical Taxonomy to identify SDG-related news topics and enables the analysis of the occurrence, intensity, and tone of sustainability issues at the country level.

I.II I created a multilayer network model in which the relationship system of countries, sustainability topics, and SDGs co-occurring in news can be analyzed using network metrics. I showed that the modules of the network are suitable for revealing communities of sustainability topics, as well as for profiling countries according to their thematic focal points and news tone. The method is suitable for identifying topic sensitivity, attention biases, and potential cooperation patterns.

I.III I highlighted that the global monitoring results based on news and network analysis can be interpreted as part of a multilevel Industry 4.0/5.0 transformation framework. Global sustainability narratives, SDG linkages, and country profiles may provide orientation for regional and organizational development priorities, while insights emerging from regional, organizational, and process-level analyses can enrich the interpretation of global sustainability patterns, benchmarks, and best practices. In the thesis, this interconnection is presented not as a separately proven result, but as an interpretive possibility of the multilevel framework.

Thesis II. I demonstrated that the developed open-data-based regional Industry 4.0 readiness model, supported by multicriteria decision methods, is suitable for assessing and revealing the regional conditions influencing the development of Industry 4.0 solutions [95].

II.I I created a NUTS-2-level, open data-based Industry 4.0+ readiness indicator system that integrates five determining dimensions of regional development and digital transformation: higher education and lifelong learning, labor market, innovation, investment, and technology. The model aggregates 101 indicators along these dimensions and, based on the Triple Helix logic, examines regional Industry 4.0 development potential.

II.II I applied multicriteria and multivariate analysis methods to construct and interpret the regional Industry 4.0+ index. Using PROMETHEE II/GAIA, PCA, SRD, and P-SRD methods, I determined regional rankings, explored the interrelationships among indicators, and identified the determining factors of regional Industry 4.0 readiness. The results of the model show associations with GDP, as well as with regional innovation and competitiveness indicators.

II.III I highlighted that the regional maturity index may function as an overarching decision-support layer connecting global sustainability and digitalization directions with organizational- and process-level Industry 4.0 developments. Regional skills, innovation capacities, technological infrastructures, labor market conditions, and investment environments determine which Industry 4.0 solutions can be introduced and scaled in a given region.

Thesis III. I demonstrated that the developed organizational decision-support methodology, based on QFD models and network science methods, is suitable for revealing the relationships between Industry 5.0 solutions and sustainability requirements [4].

III.I I demonstrated that the Quality Function Deployment (QFD) methodology is suitable for translating high-level sustainability goals and reporting requirements into organizational development tasks. The developed framework connects SDG targets, GRI Topic Standards, and Industry

5.0 solution families, complemented by Operator 4.0 and human-centric management considerations.

III.II I created bipartite network models to examine the SDG–GRI and GRI–Industry 5.0 relationship systems. Network analysis enables the exploration of the direct and indirect structural relationships between SDG targets and GRI topics, as well as between GRI topics and Industry 5.0 solution families. The method does not provide a general development direction that is uniform for all organizations; rather, it can be applied as a company- and industry-specific decision-support tool. The content, weighting, and interpretation of the relationship matrices can be adapted to the sustainability priorities, industry context, and reporting requirements of the given organization.

III.III I highlighted that the organizational-level QFD–network framework can create a connection between global SDG/ESG expectations, industry- and company-specific sustainability requirements, and process-level implementation. The method supports the transformation of global sustainability goals and reporting expectations into company-specific requirements, and then into concrete Industry 5.0 solution families, which can later become executable in the form of process models, data flows, and performance indicators.

Thesis IV. I demonstrated that the developed data-driven business process management methodology is suitable for supporting the process-level implementation and continuous improvement of Industry 4.0 solutions [6].

IV.I I showed that the business process management (BPM) lifecycle is suitable for the structured management of Industry 4.0 developments, as it connects process identification, discovery, analysis, redesign, implementation, monitoring, and control. I highlighted that Industry 4.0 tools—such as sensor data, manufacturing information systems, simulation models, and data-driven decision-support methods—can be integrated into the different phases of the BPM lifecycle.

IV.II I developed an integrated BPM–CRISP-ML(Q) guideline that embeds machine learning and data mining process models into the business process management cycle. The methodology ensures that data-driven

modeling supports process development from problem understanding to implementation and monitoring in a quality-assured, reproducible, and KPI-based manner.

IV.III I demonstrated the methodology through the redesign of a CNC production line, where BPMN-based process simulation, manufacturing data analysis, MES integration, and optimization tools jointly supported data-driven process development. Through the case study, I showed that linking BPM and Industry 4.0 tools supports process redesign and continuous improvement along measurable performance indicators.

IV.IV I highlighted that process-level data-driven BPM can be interpreted as the practical implementation layer of the previous three levels. Global sustainability focal points, regional Industry 4.0 readiness conditions, and organizational-level sustainability priorities can only become measurable development results if they are also represented at the process level in concrete data sources, KPIs, process models, and intervention points. At the same time, process-level results can be fed back in a bottom-up manner into organizational strategy, regional development practices, and the broader interpretation of Industry 4.0/5.0 transformation.

Overall, the thesis delivers a set of interlinked conceptual and methodological contributions from global monitoring tools and regional readiness indicators to organisational decision-support frameworks and process-level guidelines that together support the design, assessment and governance of Industry 4.0 and 5.0 transformations in line with sustainability and human-centric objectives.

Chapter G

Appendix

Tézisek

Tézis I. Igazoltam, hogy a fejlesztett, hír- és hálózatelemzésen alapuló eszköztár alkalmas a fenntarthatósággal kapcsolatos problémák globális szintű azonosítására és elemzésére [1].

I.I Bemutattam, hogy a világ híreinek a Fenntartható Fejlődési Célokhoz kapcsolódó taxonómiai kategóriákkal való összekapcsolásával olyan adatvezérelt monitoringrendszer alakítható ki, amely kiegészíti a hagyományos, indikátoralapú SDG-értékeléseket. A módszer a GDELT-adatbázist és a World Bank Topical Taxonomyt használja az SDG-khez kapcsolódó hírtémák azonosítására, és lehetővé teszi a fenntarthatósági kérdések előfordulásának, intenzitásának és hangvételének elemzését.

I.II Többrétegű hálózati modellt hoztam létre, amelyben az országok, a fenntarthatósági témák és a hírekben együtt előforduló SDG-k kapcsolatrendszere hálózati metrikák segítségével elemezhető. Megmutattam, hogy a hálózat moduljai alkalmasak a fenntarthatósági témák közösségeinek feltárására, valamint az országok tematikus fókuszpontok és hírhangvétel szerinti profilozására. A módszer alkalmas a témaszenzitivitás, a figyelmi torzítások és a potenciális együttműködési mintázatok azonosítására.

I.III Rámutattam, hogy a híralapú és hálózatelemzési módszereken alapuló globális monitoringeredmények egy többszintű Ipar 4.0/5.0 transzformációs keretrendszer részeként értelmezhetők. A globális fenntarthatósági

narratívák, az SDG-kapcsolódások és az országprofilok orientációt nyújthatnak a regionális és szervezeti fejlesztési prioritások számára, míg a regionális, szervezeti és folyamatszintű elemzésekből származó felismerések gazdagíthatják a globális fenntarthatósági mintázatok, benchmarkok és jó gyakorlatok értelmezését. A disszertációban ez az összekapcsolódás nem önállóan bizonyított eredményként, hanem a többszintű keretrendszer értelmezési lehetőségeként jelenik meg.

Tézis II. Igazoltam, hogy a fejlesztett, nyílt adatokra épülő regionális Ipar 4.0 felkészültségi modell, többkritériumos döntési módszerekkel támogatva, alkalmas az Ipar 4.0 megoldások fejlesztését befolyásoló regionális feltételek értékelésére és feltárására [95].

II.I Létrehoztam egy NUTS-2 szintű, nyílt adatokon alapuló Ipar 4.0+ felkészültségi indikátorrendszert, amely a regionális fejlődés és a digitális transzformáció öt meghatározó dimenzióját integrálja: felsőoktatás és élethosszig tartó tanulás, munkaerőpiac, innováció, beruházás és technológia. A modell e dimenziók mentén 101 indikátort aggregál, és a Triple Helix logikára építve vizsgálja a regionális Ipar 4.0 fejlesztési potenciált.

II.II Többkritériumos és többváltozós elemzési módszereket alkalmaztam a regionális Ipar 4.0+ index kialakítására és értelmezésére. A PROMETHEE II/GAIA, PCA, SRD és P-SRD módszerek segítségével regionális rangsorokat határoztam meg, feltártam az indikátorok közötti összefüggéseket, és azonosítottam a regionális Ipar 4.0 felkészültség meghatározó tényezőit. A modell eredményei összefüggést mutatnak a GDP-vel, valamint a regionális innovációs és versenyképességi indikátorokkal.

II.III Rámutattam, hogy a regionális érettségi index átfogó döntéstámogatási rétegként működhet, amely összekapcsolja a globális fenntarthatósági és digitalizációs irányokat a szervezeti és folyamatszintű Ipar 4.0 fejlesztésekkel. A regionális készségek, innovációs kapacitások, technológiai infrastruktúrák, munkaerőpiaci feltételek és beruházási környezetek meghatározzák, hogy egy adott régióban mely Ipar 4.0 megoldások vezethetők be és skálázhatók.

Tézis III. Igazoltam, hogy a fejlesztett, QFD-modellekre és hálózattudományi módszerekre épülő szervezeti döntéstámogató módszertan alkalmas az Ipar 5.0 megoldások és a fenntarthatósági követelmények közötti kapcsolatok feltárására [4].

III.I Bemutattam, hogy a Quality Function Deployment (QFD) módszertan alkalmas a magas szintű fenntarthatósági célok és jelentéstételi követelmények szervezeti fejlesztési feladatokká történő lefordítására. A kidolgozott keretrendszer összekapcsolja az SDG-célokat, a GRI Topic Standardokat és az Ipar 5.0 megoldáscsaládokat, kiegészítve az Operator 4.0 és az emberközpontú menedzsment szempontjaival.

III.II Bipartit hálózati modelleket hoztam létre az SDG–GRI és a GRI–Ipar 5.0 kapcsolatrendszerek vizsgálatára. A hálózatelemzés lehetővé teszi az SDG-célok és GRI-témák, valamint a GRI-témák és az Ipar 5.0 megoldáscsaládok közötti közvetlen és közvetett strukturális kapcsolatok feltárását. A módszer nem ad minden szervezet számára egységes, általános fejlesztési irányt; sokkal inkább vállalat- és iparágspecifikus döntéstámogatási eszközként alkalmazható. A kapcsolati mátrixok tartalma, súlyozása és értelmezése az adott szervezet fenntarthatósági prioritásaihoz, iparági kontextusához és jelentéstételi követelményeihez igazítható.

III.III Rámutattam, hogy a szervezeti szintű QFD–hálózati keretrendszer kapcsolatot teremthet a globális SDG/ESG elvárások, az iparág- és vállalatspecifikus fenntarthatósági követelmények, valamint a folyamatszintű megvalósítás között. A módszer támogatja a globális fenntarthatósági célok és jelentéstételi elvárások vállalatspecifikus követelményekké, majd konkrét Ipar 5.0 megoldáscsaládokká történő átalakítását, amelyek később folyamatmodellek, adatáramlások és teljesítménymutatók formájában végrehajthatóvá válhatnak.

Tézis IV. Igazoltam, hogy a fejlesztett adatvezérelt üzletifolyamat-menedzsment módszertan alkalmas az Ipar 4.0 megoldások folyamatszintű megvalósításának és folyamatos fejlesztésének támogatására [6].

IV.I Bemutattam, hogy az üzleti folyamatmenedzsment (BPM) életciklusa alkalmas az Ipar 4.0 fejlesztések strukturált menedzselésére, mivel összekapcsolja a folyamatok azonosítását, feltárását, elemzését, újratervezését, megvalósítását, monitorozását és kontrollját. Rámutattam, hogy az

Ipar 4.0 eszközei – például a szenzoradatok, a gyártási információs rendszerek, a szimulációs modellek és az adatvezérelt döntéstámogatási módszerek – integrálhatók a BPM-életciklus különböző fázisaiba.

IV.II Integrált BPM–CRISP-ML(Q) iránymutatást dolgoztam ki, amely a gépi tanulási és adatbányászati folyamatmodelleket beágyazza az üzleti folyamatmenedzsment ciklusába. A módszertan biztosítja, hogy az adatvezérelt modellezés a probléma megértésétől a megvalósításig és monitorozásig minőségbiztosított, reprodukálható és KPI-alapú módon támogassa a folyamatfejlesztést.

IV.III A módszertant egy CNC gyártósor újratervezésén keresztül demonstráltam, ahol a BPMN-alapú folyamatszimuláció, a gyártási adatelemzés, a MES-integráció és az optimalizációs eszközök együttesen támogatták az adatvezérelt folyamatfejlesztést. Az esettanulmányon keresztül megmutattam, hogy a BPM és az Ipar 4.0 eszközök összekapcsolása mérhető teljesítménymutatók mentén támogatja a folyamatok újratervezését és folyamatos fejlesztését.

IV.IV Rámutattam, hogy a folyamatszintű adatvezérelt BPM az előző három szint gyakorlati megvalósítási rétegeként értelmezhető. A globális fenntarthatósági fókuszpontok, a regionális Ipar 4.0 felkészültségi feltételek és a szervezeti szintű fenntarthatósági prioritások csak akkor válhatnak mérhető fejlesztési eredményekké, ha a folyamatszinten is megjelennek konkrét adatforrásokban, KPI-okban, folyamatmodellekben és beavatkozási pontokban. Ugyanakkor a folyamatszintű eredmények alulról felfelé visszacsatolhatók a szervezeti stratégiába, a regionális fejlesztési gyakorlatokba és az Ipar 4.0/5.0 transzformáció tágabb értelmezésébe.

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