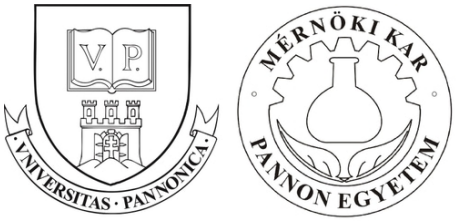
Theses of PhD dissertation

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

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Veszprém
2026

Introduction to the topic

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. 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. 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.

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.

Research objectives

The overall objective of this research is to develop data- and systems-science-based frameworks that support the analysis, planning, prioritization, and implementation of sustainable Industry 4.0 and Industry 5.0 transformation across multiple decision levels.

- Global level: To develop a news- and network-analysis-based monitoring framework for identifying SDG-related topics, country profiles, news tone, and co-occurrence structures.
- Regional level: To develop an open-data-based Industry 4.0+ readiness model and transparent ranking methodology for European NUTS-2 regions.
- Organizational level: To develop a QFD- and network-analysis-based decision-support framework that connects sustainability requirements with Industry 5.0 solution families and supports company- and industry-specific prioritization.
- Process level: To develop and demonstrate a data-driven BPM and CRISP-ML(Q)-based framework for process redesign, implementation, monitoring, and continuous improvement.
- Multi-level: To provide a conceptual multi-level interpretation of the four level-specific frameworks and to examine their complementary roles in sustainability-oriented Industry 4.0 and

5.0 transformation, including the top-down relationships through which higher-level priorities can be interpreted in regional, organizational, and process-level contexts, and the bottom-up feedback logic through which lower-level insights can inform higher-level perspectives.

Research questions and frameworks

The research is structured around the multi-scale framework shown in Figure 1. Each level is discussed more in detail in the following paragraphs. In Figure 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.

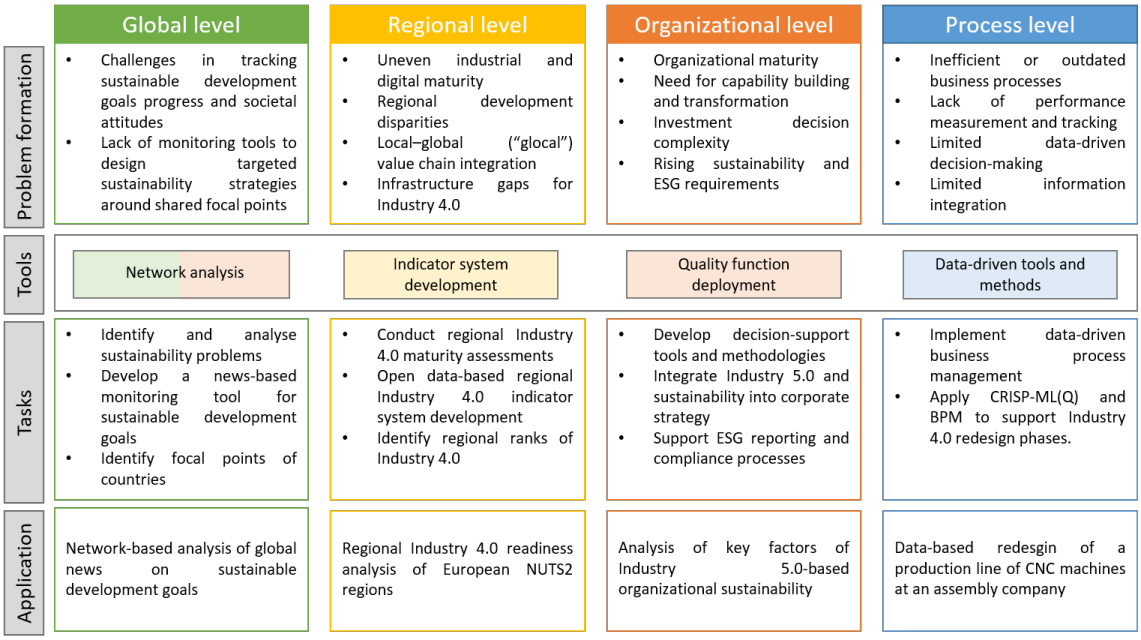


Figure 1: Schematic framework of the research topics (Source: author's own work)

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 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 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 can organizations 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 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.

Results

The scientific results and contribution of my research is formed in four theses, each corresponding to one analytical level and underpinned by publications. Thesis statements are presented below.

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 [2].

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 [3].

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 [4].

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.

Publications related to the thesis

1. T. Czvetko, G. Honti, V. Sebestyen, J. Abonyi, The intertwining of world news with sustainable development goals: An effective monitoring tool, Heliyon 7 (2) (2021).

2. T. Czvetko, G. Honti, J. Abonyi, Regional development potentials of industry 4.0: Open data indicators of the industry 4.0+ model, PLOS ONE 16 (4) (2021) e0250247

3. T. Czvetko, V. Sebestyen, J. Abonyi, Key factors of industry 5.0-based organizational sustainability, Technology in Society (2025) 102966.

4. T. Czvetko, A. Kummer, T. Ruppert, J. Abonyi, Data-driven business process management-based development of industry 4.0 solutions, CIRP journal of manufacturing science and technology 36 (2022) 117–132.

Publications not related to the thesis

1. Abonyi, J., Czvetkó, T., & Honti, G. M. (2020). Are regions prepared for industry 4.0?: the industry 4.0+ indicator system for assessment. Springer Nature.

2. Honti, G., Czvetkó, T., & Abonyi, J. (2020). Data describing the regional Industry 4.0 readiness index. Data in Brief, 33, 106464.

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