Bridging the Gap Between Industry 4.0 Readiness and Maturity Assessment Models: An Ontology-Based Approach

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***Abstract*—The rapid evolution of Industry 4.0 technologies has created a complex and interconnected landscape of readiness and maturity assessment models. However, these models often fail to address the full spectrum of organizational readiness across strategic, technological, operational, and cultural dimensions, while also not accounting for emerging paradigms such as Industry 5.0. This paper proposes a conceptual model for an ontology that integrates all relevant domain knowledge into a unified framework, capturing strategic, technological, operational, and cultural readiness and maturity within a single comprehensive model. The ontology provides a systematic approach to understanding the interconnectedness of I4.0 and Industry 5.0 assessment models, facilitating a holistic view of an organization's preparedness for digital transformation. By bridging the gap between these two stages of industrial evolution, the model enables interoperability across diverse frameworks, promoting more informed decision-making and strategic planning. This research highlights the potential of the proposed ontology to support the ongoing shift from Industry 4.0 to Industry 5.0, offering a valuable tool for researchers, practitioners, and decision-makers navigating the complexities of next-generation industrial ecosystems. The paper further discusses the theoretical underpinnings and practical applications of the model in fostering a smooth transition toward a more human-centric, sustainable, and technologically advanced industrial future.**

Keywords*—Industry 4.0; readiness assessment; maturity assessment; digital transformation; ontology development; conceptual model; knowledge engineering

I. Introduction

The rapid advancement of Industry 4.0 technologies has brought transformative changes to manufacturing and industrial operations, enabling organizations to achieve unprecedented levels of efficiency, flexibility, and competitiveness [1, 2, 3, 4]. By integrating technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, cloud computing, and cyber-physical systems, Industry 4.0 represents a paradigm shift in how industries operate and innovate [3]. However, the successful adoption of these technologies requires more than technical implementation; it demands a comprehensive understanding of organizational readiness across multiple dimensions, including technology, workforce, processes, and strategy.

Assessing readiness and maturity for Industry 4.0 is critical for organizations to identify their current capabilities, recognize gaps, and prioritize efforts to address them. Traditional readiness assessment approaches, such as the IMPULS and SIRI frameworks [4, 5], provide valuable starting points by identifying key dimensions and establishing readiness levels. However, these models often rely on static evaluations and qualitative surveys, limiting their ability to provide real-time insights or address the interconnected nature of Industry 4.0 dimensions. Their lack of reasoning capabilities results in assessments that may overlook nuanced interdependencies between readiness factors, leading to generalized or incomplete recommendations.

To address these limitations, this paper proposes an ontology-based framework for assessing Industry 4.0 readiness. Ontologies offer a structured and formal representation of knowledge, enabling the modeling of complex and dynamic domains. The proposed framework captures key readiness dimensions, including connectivity, digital infrastructure, cybersecurity, workforce capabilities, strategy, and data analytics. It also intends to integrate in next steps reasoning capabilities through the Semantic Web Rule Language. This innovative approach automates the inference of readiness levels based on organization-specific input data, ensuring consistency, transparency, and scalability.

The use of ontology and reasoning mechanisms provides several benefits. It not only standardizes the assessment process but also generates actionable insights by uncovering the interdependencies between readiness dimensions. For instance, the framework can identify how gaps in workforce skills might affect the effective deployment of digital infrastructure or how a lack of cybersecurity measures could hinder data analytics capabilities. By offering dynamic and tailored recommendations, the framework empowers organizations to make data-driven decisions, strategically allocate resources, and accelerate their digital transformation.

This article is structured as follows. First, a review of existing Industry 4.0 readiness models highlights their contributions and limitations, establishing the need for an ontology and rule based reasoning approach. Next, Section III methodology for developing the ontology, including the design of its classes, properties, and conceptual models. This is followed by a detailed discussion of the theoretical underpinnings and practical applications of the model in fostering a smooth transition toward a more human-centric, sustainable, and technologically advanced industrial future in Section IV. Finally, the paper is concluded in Section V.

II. Related Work

This section reviews the fundamental concepts and characteristics of Industry 4.0, its requirements and enabling technologies, and the existing readiness models that evaluate the preparedness and implementation of Industry 4.0.

A. Industry 4.0 Overview and Characterization

The term Industry 4.0 originated in Germany, specifically in Hannover in 2011, marking the transformative potential of integrated technologies in reshaping global value chains. This initiative highlighted the possibilities of product customization and novel production methods [6], facilitated by the interaction of technologies across physical, digital, and biological domains. This fusion marks a distinct advancement in the fourth industrial revolution compared to its predecessors.

According to the Germany Trade and Invest Institute [7], Industry 4.0 represents a technological leap from embedded systems to cyber-physical systems (CPSs), leveraging the power of the Internet, data, and services. In this paradigm, industrial machinery evolves to not only process products but also enable communication between products and machinery, effectively directing the production process. Industry 4.0 represents a transformative leap forward in manufacturing, characterized by the integration of advanced technologies and their constant interaction across physical, digital, and biological domains.

It marks a new maturity stage for manufacturing companies, leveraging technologies such as the Internet of Things (IoT), Cloud Computing (CC), Big Data (BD), Artificial Intelligence (AI), and Cyber-Physical Systems (CPSs) to create interconnected, intelligent production environments. These systems enable real-time decision-making, remote monitoring, and flexible modular production processes [6-9]. To implement Industry 4.0, several main features are identified that support the evolution of intelligent production systems [10]:

- Interoperability, Integrity, and Awareness: The degree of system collaboration in utilizing capabilities, sharing information, and intelligent decision-making [11].
- Virtualization: Enabling remote traceability and monitoring of processes through sensors, creating smart factories.
- Service Orientation: Utilizing service-oriented software alongside IoT technologies.
- Real-Time Operation Capability: Facilitating instant data gathering, processing, and decision-making.
- Modularity: Flexible production processes involving the coupling and decoupling of production modules.
- Decentralization: Allowing CPSs to make independent decisions and produce locally, utilizing technologies like 3D printing.

The integration of these features is made possible by enabling technologies. For instance, IoT involves billions of interconnected devices like sensors and industrial equipment, facilitating real-time data collection and analysis [2,10].AI plays a central role in enabling Industry 4.0 by integrating intelligent functionalities across the value chain, from customer acquisition to operations management [3,4,9]. Moreover, big data and cloud computing address the exponential growth of data generated in manufacturing, offering scalable solutions for data storage, analysis, and processing.

The exponential growth of data in Industry 4.0 often exceeds human processing capabilities. Cloud Computing (CC) addresses this challenge by offering shared, on-demand resources via the Internet, delivering high-quality services at reduced costs [4, 9]. Simultaneously, Big Data (BD) enhances decision-making by analyzing vast amounts of information characterized by volume, velocity, variety, and veracity [4]. In addition to enabling technologies, Industry 4.0 fosters smarter work environments where technologies enhance human capabilities rather than replace them. Meindl et al. [12] emphasize that advanced systems support decision-making, creativity, and safety, leading to smarter workplaces. This human-centric approach has given rise to discussions around Industry 5.0 [13], which emphasizes workers' central role in digital transformation.

Industry 4.0 is more than the adoption of cutting-edge technologies; it’s about connecting these technologies to foster organizational growth and operational efficiency [14]. By leveraging advanced technologies like robotics, additive manufacturing, and analytics, companies can drive innovation, improve customer experiences, and enable predictive decision-making. For instance, smart products and connected systems enhance customer interactions through enriched post-sales support and tailored marketing strategies [15].

However, the implementation of Industry 4.0 varies widely based on organizational readiness, technological infrastructure, and economic development. Developing nations often face challenges in adopting these technologies while maintaining competitive advantage [16, 17]. Organizations must navigate talent development, process changes, and strategic human resource management to align with Industry 4.0 demands [18,19]. Readiness and Maturity models serve as valuable tools in assessing current adoption levels and guiding strategic implementation efforts.

B. Industry 4.0 Readiness and Maturity Models

The emergence of Industry 4.0 has prompted the development of numerous readiness and maturity models, each aiming to assess and guide organizations through their transformation journeys. While these models have made significant contributions to understanding readiness, they also exhibit notable limitations, particularly in terms of validation, granularity, and cross-industry applicability. Table I reviews prominent Industry 4.0 readiness models and identifies gaps that motivate the proposed ontology based readiness assessment smart system.

TABLE I. ANALYSIS OF EXISTING INDUSTRY 4.0 READINESS AND MATURITY MODELS

Model Name	Ref	Country	Contribution	Focus Areas
ACATECH I4.0 Maturity Index	[20]	Germany	Six-level progression emphasizing adaptability through technology and organization integration.	Technology & organization integration
IMPULS Industrie 4.0 Readiness	[21]	Germany	Practical tool tailored for German manufacturing industries.	Manufacturing industries
Singapore Smart Industry Readiness Index	[22]	Singapore	Comprehensive framework with 16 dimensions under three pillars: process, technology, and organization.	Holistic transformation
6Ps Maturity Model for SMEs	[23]	Italy	Tailored to SMEs, addressing unique small enterprise challenges with six stages.	SME-specific
Integrated IoT Capability Maturity Model	[24]	Netherlands	Combines capabilities from diverse frameworks to improve IoT management through five stages.	IoT management
SIMMI 4.0	[25]	Germany	Structured focus on digitization levels and integration across technologies and departments.	Digitization & IT integration
Industry 4.0 Readiness and Maturity Model	[26]	Austria	Comprehensive framework with nine dimensions, including strategy, leadership, governance, and innovation.	Technological & organizational aspects
Maturity Model for Smart Manufacturing	[27]	Turkey / Cyprus	Modular and incremental design adaptable to manufacturing contexts.	Modular for manufacturing
Categorical Framework of Manufacturing	[28]	United Kingdom	Multi-level approach integrating intelligence and automation across four dimensions.	Intelligence & automation

The ACATECH I4.0 Maturity Index [20] outlines a six-level progression from computerization to adaptability, emphasizing the integration of technological and organizational capabilities. This theoretical framework offers a structured approach to transformation but remains limited to conceptual discussions without cross-industry validation or practical implementation examples. Its lack of application-oriented guidance reduces its relevance for diverse industrial contexts. The IMPULS Industrie 4.0 Readiness model [21] assesses readiness across six dimensions: strategy, organization, IT infrastructure, smart products, smart services, and employees. It provides practical tools for manufacturing industries, particularly in Germany, making it highly relevant for this sector. However, its sector-specific focus restricts its versatility, limiting its applicability to other industries or global contexts.

The Singapore Smart Industry Readiness Index [22] provides a comprehensive framework encompassing 16 dimensions across three pillars: process, technology, and organization. Its holistic approach and intuitive tools are valuable for readiness assessment. Nevertheless, the model lacks extensive validation across sectors and does not provide detailed action plans for achieving specific maturity levels, reducing its utility for organizations seeking granular guidance. The 6Ps Maturity Model for SMEs [23] is tailored to address the unique challenges of small and medium enterprises (SMEs). With six stages: Plan, Prepare, Predict, Produce, Promote, and Proliferate. The model has been validated through case studies involving nine SMEs. However, its applicability to larger enterprises or different industrial contexts remains underexplored, highlighting a need for broader adaptability. The Integrated IoT Capability Maturity Model [24] combines capabilities from various frameworks to improve IoT management through five stages, ranging from primitive to maximizing, and three dimensions: technology, authority & culture, and knowledge management. While its operational focus on IoT is notable, the absence of practical validation and its narrow scope limit its broader relevance in the Industry 4.0 landscape. SIMMI 4.0 [25] emphasizes digitization and IT integration, guiding organizations through five maturity stages, from basic to optimized full digitization. Its focus on vertical and horizontal integration, cross-technology criteria, and digital product development provides a robust framework for IT landscapes. However, it neglects critical factors such as organizational culture and employee readiness, which are essential for successful Industry 4.0 adoption.

The Industry 4.0 Readiness and Maturity Model [26] offers a comprehensive framework with nine dimensions, including strategy, leadership, governance, and innovation. This balanced approach to technological and organizational readiness has been validated through a manufacturing case study. However, the complexity of its framework poses challenges for smaller enterprises, making adoption difficult without significant resources. The Maturity Model for Smart Manufacturing [27] adopts a modular and incremental design, making it adaptable to various manufacturing contexts. It evaluates five key dimensions: strategy, leadership, technology, culture, and operations. While validated through a case study, the model\u2019s scalability to larger enterprises and applicability in non-manufacturing sectors are not well explored. The Categorical Framework of Manufacturing [28] integrates intelligence and automation across four dimensions: factory, business, process, and customers. This multi-level framework offers a comprehensive perspective on readiness. However, its lack of practical examples and detailed guidance for progression limits its effectiveness and real-world applicability.

Despite the diverse contributions of these models, significant limitations persist. Many models focus heavily on technological aspects, such as digitization and IoT integration, while overlooking critical organizational factors like culture, leadership, and employee readiness. Additionally, most frameworks are constrained by sector-specific designs, limiting their adaptability to different industries. The lack of practical validation and real-world case studies further hampers their utility, as organizations struggle to translate theoretical guidance into actionable strategies. Moreover, the absence of reasoning-based approaches reduces their ability to dynamically adapt to evolving industrial contexts, creating a gap for more intelligent and flexible assessment tools.

Existing Industry 4.0 readiness models provide valuable insights but fail to address the need for holistic, adaptive, and validated frameworks. To overcome these challenges, this paper proposes an ontology-driven framework incorporating reasoning mechanisms to enable dynamic and adaptive readiness assessment. This approach aims to offer a more comprehensive and actionable tool for Industry 4.0 transformation across diverse industries and organizational contexts.

III. Conceptual Model Development Methodology

This section outlines the methodology employed to construct a robust ontology specifically designed for Industry 4.0, along with its corresponding conceptual model. Recognizing the interdependence between these two components, the development process adopts a systematic and strategic approach to conceptualization. The conceptual model, which serves as the foundation for ontology development, provides a clear and visual representation of the domain, facilitating better understanding and usability. Moreover, the model is designed to be reusable, allowing adaptation across various ontology representation languages. The methodology applied here is informed by well-established practices in ontology development, tailored to address the unique characteristics and challenges of Industry 4.0.

To achieve this, a hybrid methodology was employed, integrating elements from different prominent approaches: the Uschold and King methodology [29], METHONTOLOGY [30] and Ontology Development [31]. Specifically, the structured framework proposed by Uschold and King was combined with the iterative processes of Ontology Development 101 and further enriched by the conceptualization techniques outlined in METHONTOLOGY.

This hybrid approach leverages the strengths of each methodology. The Uschold and King framework offers a systematic starting point for constructing the ontology's initial structure. Ontology Development 101 introduces iterative refinement, enabling detailed and comprehensive development. The inclusion of METHONTOLOGY ensures a deep understanding of the domain through its emphasis on conceptualization, ensuring that the model accurately captures the semantics of Industry 4.0.

The construction of the conceptual model followed a series of structured steps:

1) Define the domain, scope, and purpose: This step establishes clear boundaries and objectives for the ontology, ensuring it aligns with the specific requirements of Industry 4.0 readiness assessment.

2) Capture knowledge and develop conceptualization: Through iterative refinement, the following tasks were performed:

Identifying key terms and concepts relevant to Industry 4.0, such as smart factories, cyber-physical systems, IoT, and advanced analytics.

Defining classes and their hierarchical relationships to represent the domain's structure.

Establishing object and data properties to define relationships and attributes within the domain.

3) Create the conceptual model: The captured knowledge was transformed into a graphical representation, ensuring clarity and reusability. The model was designed to reflect core aspects of Industry 4.0, such as interoperability, automation, and digital transformation.

Fig. 1 illustrates the workflow adopted in this methodology, demonstrating the integration of the selected approaches and their application to Industry 4.0 ontology development.

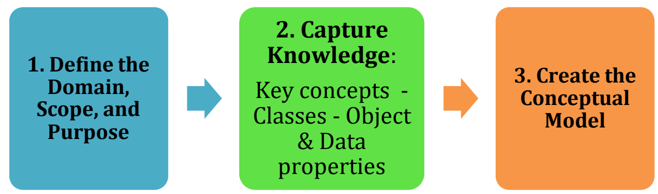

Fig. 1. The workflow of the ontology conceptual model development methodology.

B. Domain, Scope, and Purpose Definition

In developing our ontology for Industry 4.0 readiness assessment, the first step is to define the domain, scope, and purpose clearly. The domain centers on Industry 4.0, specifically focusing on the readiness and maturity of industrial companies in adopting advanced technologies and practices. The scope includes dimensions such as technological capabilities, organizational processes, workforce skills, and strategic alignment while excluding unrelated areas like consumer behaviors or non-industrial sectors.

The purpose of this ontology, as presented in Table II, is to provide a structured framework for evaluating and comparing the readiness of companies for Industry 4.0 transformation, facilitating informed decision-making and guiding improvement strategies. This step ensures that the ontology is both focused and relevant, addressing the key challenges and requirements of stakeholders in the Industry 4.0 landscape.

C. Capturing Knowledge and Conceptualization Definition

1) Identifying key terms and concepts: The process of capturing knowledge within the context of Industry 4.0 readiness involves identifying the core elements that influence an organization's journey toward digital transformation. This is achieved through the use of an ontology, which structures and organizes these elements into defined categories that enable clearer understanding, assessment, and decision-making. The conceptualization phase takes these elements and translates them into formal representations, allowing them to be analyzed and applied practically across industries. Our ontology is structured around four main dimensions: Strategic, Technological, Operational, and Cultural as presented in Fig. 2.

TABLE II. SCOPE, DOMAIN AND KNOWLEDGE SOURCE OF THE INDUSTRY 4.0 ASSESSMENT ONTOLOGY

Domain	**The domain of interest of this work is industry 4.0 readiness and maturity**
Date	2024-2025
Purpose	• Establish a standardized framework for organizing and categorizing Industry 4.0 readiness data, ensuring consistency and comparability across evaluations. • Enable reasoning to infer implicit knowledge, identify gaps in readiness, and derive automated recommendations for targeted improvements. • Facilitate evidence-based decision-making by linking readiness dimensions to actionable strategies, prioritizing critical areas, and enabling benchmarking. • Provide adaptability for evolving Industry 4.0 practices by integrating new concepts, technologies, and criteria as the domain progresses. • Support cross-functional and cross-organizational alignment by offering a shared vocabulary for clear communication and collaboration. • Serve as a foundational tool for advancing research, enabling data-driven insights, and fostering innovation in Industry 4.0 readiness assessments and practices.
Scope	The scope of the ontology is to provide a structured framework for assessing and auditing industrial companies' readiness for Industry 4.0 transformation across strategic, technological, operational, and cultural dimensions, enabling organizations to benchmark their progress, identify gaps, and guide their digital transformation journey.
Source of Knowledge	• ACATECH I4.0 Maturity Index [20] • IMPULS Industry 4.0 Readiness [21] • Singapore Smart Industry Readiness Index [22] • 6Ps Maturity Model for SMEs [23] • Integrated IoT Capability Maturity Model [24] • SIMMI 4.0 [25] • Industry 4.0 Readiness and Maturity Model [26] • Maturity Model for Smart Manufacturing [27] • Categorical Framework of Manufacturing [28] • Reference Architecture Model for Industry 4.0 • Surveys and Case Studies from Leading Manufacturers • Reports and Whitepapers from Industry Associations • Public Sector Digital Transformation Initiatives • Interviews and Insights from Technology Providers

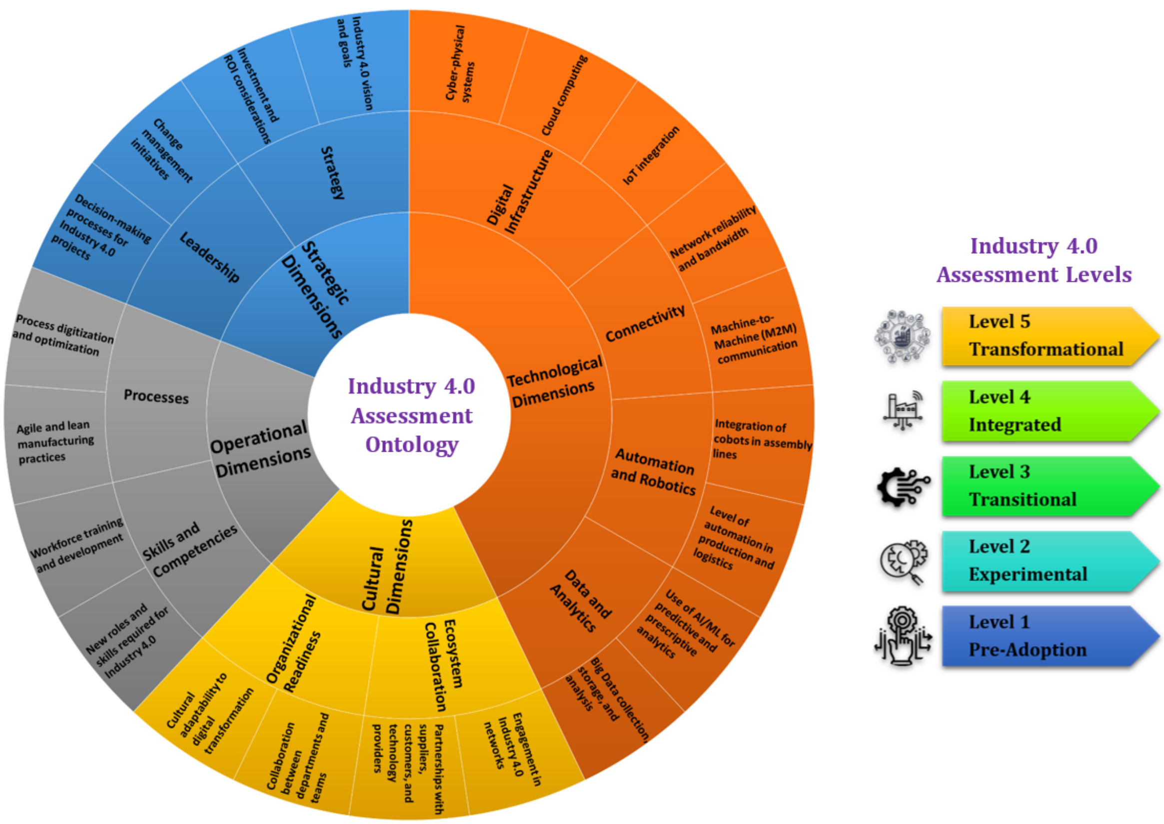

Fig. 2. Dimensions, associated fields and evaluation levels of the proposed industries 4.0 assesment ontology.

2) Capture knowledge and develop conceptualization: The assessment dimensions encompass the essential factors that determine an organization's preparedness for Industry 4.0 adoption. Within each dimension, specific classes are defined to capture the knowledge associated with different aspects of transformation. For instance, the Strategic Dimensions contain classes such as Strategy, which represents the company's approach to aligning its goals with Industry 4.0, ranging from early awareness to full integration. Similarly, Leadership in this dimension reflects varying stages of leadership involvement, from lack of awareness to driving an innovation culture.

In the Technological Dimensions, the ontology includes classes such as Digital Infrastructure, which captures the evolution of IT systems from basic setups to fully integrated, smart manufacturing solutions. Classes like Processes, Data and Analytics, and Automation and Robotics represent the increasing sophistication of processes, data utilization, and automation in an Industry 4.0 environment. Each of these classes models the different stages of digital transformation in terms of technology adoption, from initial automation trials to the use of AI and machine learning in decision-making processes.

The Operational Dimensions focus on the organization's day-to-day operations, particularly the level of connectivity within the enterprise. The Connectivity class, for example, spans from isolated devices to seamless, real-time communication across the organization, while the Workforce Skills class tracks the evolution of employee competencies, capturing the transition from basic awareness to continuous adaptation of advanced digital skills. Finally, the Cultural Dimensions include classes like Organizational Readiness, which represents the organization's cultural alignment with Industry 4.0 principles. This class captures the evolution from resistance to change to a fully agile and innovation-driven environment. Additionally, the Ecosystem Collaboration class addresses the growing importance of strategic partnerships, from no collaboration to leadership in collaborative networks within the industry.

The conceptualization of the ontology involves translating these real-world concepts into formal classes and defining relationships between them. For example, Leadership is conceptualized as a class that influences both Strategy and Organizational Readiness, with relationships indicating how leadership's engagement drives the alignment of strategy and cultural transformation. Each class is further defined with specific properties and attributes, representing the maturity levels or stages of development. In the Strategy class, for instance, these properties might range from "Initial Exploration" to "Fully Aligned Corporate Strategy," reflecting different levels of maturity in aligning the company's strategy with Industry 4.0 goals. As part of the knowledge capture process, the ontology also formalizes the data collection methods that link these conceptualized classes to real-world assessments. This allows organizations to map their existing capabilities against the maturity levels defined in the ontology, offering a detailed picture of their current readiness. For example, Workforce Skills can be tied to specific skill data collected through employee assessments, training programs, and competency evaluations.

3) Create the conceptual model: The conceptualized ontology forms the basis of structured audits and assessments of Industry 4.0 readiness. By representing the different stages of maturity in each class, it allows organizations to pinpoint their strengths and weaknesses, identifying areas where they need to improve. This structured approach to capturing and organizing knowledge ensures that the assessment process is objective, repeatable, and aligned with the overall goal of driving digital transformation within industrial settings. The conceptualization phase, therefore, not only organizes knowledge but creates a dynamic framework for ongoing evaluation, facilitating continuous progress toward Industry 4.0. In fact in this stage, we defined not only the relations between the different classes but also the details on the minimum requirements for each maturity level in our model as represented in Fig. 3.

Industry 4.0 Assessment Dimensions		Level 1 Pre-Adoption	Level 2 Experimental	Level 3 Transitional	Level 4 Integrated	Level 5 Transformational
Strategic Dimensions	Strategy	No formal Industry 4.0 strategy or awareness.	Initial exploration of Industry 4.0 opportunities and risks.	Defined strategy with clear milestones.	Fully aligned corporate strategy with Industry 4.0 goals.	Continuous evolution of strategy based on innovation and market trends.
	Leadership	Leadership lacks awareness or engagement in Industry 4.0.	Leadership explores pilot initiatives and starts allocating budget.	Leaders actively drive initiatives and engage teams.	Leadership ensures organization-wide commitment and resource allocation.	Leadership promotes innovation culture and global thought leadership.
Technological Dimensions	Digital Infrastructure	Basic IT systems with minimal automation or connectivity.	Isolated systems and initial pilot setups for IoT or cloud computing.	Moderate IT integration; emerging IoT networks and cloud usage.	Fully integrated systems with real-time data access and decision-making.	Adaptive and scalable systems, leveraging edge computing and advanced networks.
	Processes	Highly manual processes with minimal standardization.	Early-stage digitalization of selected processes.	Processes are increasingly digitized and standardized across units.	Digital and optimized processes; cross-departmental collaboration.	Adaptive and self-optimizing processes with AI-driven automation.
	Data and Analytics	Minimal data collection; analysis is manual or nonexistent.	Basic data collection for pilot projects; spreadsheets or simple tools used.	Systematic data collection and some use of business intelligence tools.	Advanced analytics with AI/ML for predictive insights across operations.	Prescriptive analytics and autonomous decision-making are fully implemented.
	Automation and Robotics	Little or no automation; reliance on manual labor.	Robotics or automation applied in isolated tasks or areas.	Semi-automated processes with robotic integration in key operations.	High level of automation in core operations, including cobotic systems.	Fully autonomous production systems with cyber-physical integration.
Operational Dimensions	Connectivity	No machine-to-machine (M2M) or IoT connectivity.	Isolated devices connected in pilot projects.	Partial connectivity across production lines or departments.	Organization-wide IoT and M2M communication for seamless data flow.	Ubiquitous connectivity enabling real-time, cross-enterprise collaboration.
	Workforce Skills	Workforce lacks Industry 4.0 awareness and skills.	Limited upskilling initiatives in response to pilot projects.	Training programs are in place; workforce acquires basic digital competencies.	Comprehensive training and workforce adaptability to Industry 4.0 demands.	Workforce continuously evolves with advanced skills; innovation-driven roles.
Cultural Dimensions	Organizational Readiness	Resistance to change; no alignment with Industry 4.0 objectives.	Isolated initiatives with some departmental support.	Organization shows buy-in and cross-departmental collaboration improves.	Entire organization is aligned and agile, supporting Industry 4.0 objectives.	Agile, innovation-focused culture with strong collaboration and change management.
	Ecosystem Collaboration	No collaboration with external partners for Industry 4.0 initiatives.	Initial partnerships for pilot projects or technology trials.	Active collaboration with select suppliers, customers, and tech providers.	Strong partnerships and ecosystem participation for mutual growth.	Strategic leader in Industry 4.0 networks; driving standards and innovation.

Fig. 3. The proposed industry 4.0 assessment model for the four dimensions – minimum requirments.

IV. Industry 4.0 Assessment Ontology Conceptual Model: Unveiling the Interconnected Landscape of Industry 4.0 Assessment Models

The Industry 4.0 readiness assessment ontology is designed to evaluate and track the maturity of organizations in their adoption of Industry 4.0 technologies. The ontology is structured around several key dimensions, as presented in Tables III and IV that represent critical aspects of organizational readiness, with each dimension encompassing various sub-dimensions, attributes, and functions to holistically assess an organization's progress and capabilities in adopting Industry 4.0 principles. These dimensions are organized into four main categories: Strategic Dimensions, Technological Dimensions, Operational Dimensions, and Cultural Dimensions.

To assess the Strategic readiness, the Strategy sub-dimension captures the organization's preparedness and strategic direction towards Industry 4.0 adoption. Key attributes include strategyLevel, which categorizes the organization's strategy (e.g., Pre-Adoption, Experimental), and awareness, which assesses the level of understanding about Industry 4.0 technologies. The milestones attribute tracks the significant stages in the organization's adoption journey. The associated functions like defineStrategy() and evaluateProgress() allow for dynamic updates and evaluation of the organization's strategic alignment with Industry 4.0 goals. The Leadership sub-dimension focuses on the commitment and engagement of leadership in driving the Industry 4.0 transformation. The attributes engagementLevel, budgetAllocation, and innovationCulture reflect leadership's role in fostering technological adoption. Functions such as assessLeadershipCommitment() and promoteInnovation() evaluate leadership's contribution to innovation and resource allocation.

TABLE III. Description of the Industry 4.0 Assessment Ontology Main Classes

Class	Description
Industry4.0ReadinessAssessment	Represents the overall assessment process to evaluate a company's Industry 4.0 readiness.
Dimension	Represents a high-level category of readiness, such as Strategy, Technology, or Operations.
Strategic Dimensions	Represents the readiness related to strategy and leadership.
Criteria: Strategy	Evaluates the existence and maturity of Industry 4.0 strategy in the organization.
Criteria: Leadership	Assesses leadership involvement and vision in adopting Industry 4.0 technologies.
Technological Dimensions	Represents readiness related to infrastructure, processes, data, and automation.
Criteria: Digital Infrastructure	Assesses the maturity of IT systems, connectivity, and integration.
Criteria: Connectivity	Evaluates the integration of IoT and machine-to-machine communication.
Criteria: Data and Analytics	Measures the ability to collect, analyze, and use data for decision-making.
Criteria: Automation and Robotics	Assesses the level of automation, including robotics and cobotics integration.
Operational Dimensions	Represents the readiness of operations, workforce, and connectivity.
Criteria: Processes	Evaluates the level of digitization and optimization in organizational processes.
Criteria: Workforce Skills	Measures the readiness and adaptability of the workforce to Industry 4.0 changes.
Cultural Dimensions	Represents readiness in terms of organizational readiness and external collaboration.
Criteria: Organizational Readiness	Assesses the organization's openness and alignment with Industry 4.0 objectives.
Criteria: Ecosystem Collaboration	Measures the level of partnership and collaboration within Industry 4.0 ecosystems.
Indicator	Represents the quantitative or qualitative measures used to evaluate a Criterion.
AssessmentResult	Captures the outcome of the readiness assessment, including scores and detailed feedback.
Company	Represents the organization being assessed for Industry 4.0 readiness.

TABLE IV. Description of the Industry 4.0 Assessment Ontology main Properties

Property Name	Domain	Range	Cardinality	Inverse Property
aggregates	Industry4.0ReadinessAssessment	Dimension	Multiple : A single Industry4.0ReadinessAssessment can aggregate multiple Dimensions.	-
hasCriteria	Dimension	Criteria	Multiple : Each Dimension must have at least one associated Criteria, but it can have multiple criteria.	isCriteriaOf
isEvaluatedUsing	Criteria	Indicator	Single : A single Criteria is evaluated using one or more Indicators.	evaluates
generates	Industry4.0ReadinessAssessment	AssessmentResult	An Industry4.0ReadinessAssessment generates exactly one AssessmentResult. This ensures that each assessment leads to a unique, consolidated result.	isGeneratedBy
isAssociatedWith	Company	Industry4.0Readiness Assessment	Multiple : A single Company can be associated with one or more Industry4.0ReadinessAssessments. This allows a company to conduct multiple assessments over time or for different operational units.	isCompanyOf

In order to assess the technological readiness and maturity, the Digital Infrastructure sub-dimension assesses the foundational technological components necessary for Industry 4.0. It includes attributes like systemIntegrationLevel, which measures the extent to which systems are integrated within the organization, and realTimeAccess and scalability, which evaluate the system's ability to handle real-time data and scale accordingly. The functions integrateInfrastructure() and evaluateInfrastructureReadiness() provide methods for enhancing and assessing the state of technological infrastructure. The Processes sub-dimension examines the degree of process optimization, with attributes such as standardization, digitizationLevel, and crossDeptCollaboration. Functions like analyzeProcessMaturity() and optimizeProcesses () allow for the assessment and improvement of business processes through digital transformation.

The Data and Analytics sub-dimension addresses data management and analytics capabilities within the organization. Key attributes include dataCollection, analyticsCapability, and predictiveAnalyticsUsage. The functions collectData() and generateInsights() help organizations manage data collection and derive valuable insights for decision-making. The Automation and Robotics sub-dimension evaluates the automation and robotics capabilities within the organization. The attributes automationLevel, coboticsUsage, and integrationComplexity allow organizations to assess their automation maturity. The functions evaluateAutomation() and implementRobotics() guide the improvement and integration of robotic systems into operations.

For the Operational assessment, the Connectivity sub-dimension is central to evaluating the effectiveness of data exchange across systems. It includes attributes like connectivityLevel, iotNetworks, and dataFlowEfficiency. Functions such as ensureSeamlessConnectivity() and evaluateNetworkPerformance() ensure that connectivity is optimized and functioning at a level necessary for Industry 4.0 operations. The Workforce Skills sub-dimension evaluates the workforce's readiness for Industry 4.0. Attributes such as trainingPrograms, skillCompetency, and upskillingFrequency measure the organization's commitment to continuous workforce development. Functions like analyzeSkillGap() and designTrainingProgram() ensure that the workforce remains competitive and capable of handling Industry 4.0 challenges.

For the cultural readiness and maturity, the Organizational Readiness sub-dimension examines cultural factors such as changeResistance, departmentalAlignment, and readinessLevel. These attributes help measure the internal alignment and the organization's preparedness to embrace change. Functions such as fosterAlignment() and assessCulturalReadiness() aim to promote cultural alignment across departments. The Ecosystem Collaboration sub-dimension explores the organization's external engagement and collaboration with partners. Attributes like partnerships, externalEngagement, and innovation Contribution gauge the organization's collaborative efforts with external stakeholders. The functions buildPartnerships() and evaluateCollaborationImpact() help foster and assess the impact of external collaborations.

A. Theoretical Implications of the Conceptual Model on the Research Landscape of Industry 4.0 Readiness and Maturity Models

The conceptual model of the Industry 4.0 readiness ontology contributes significantly to the theoretical discourse on maturity and readiness models in Industry 4.0. By systematically integrating strategic, technological, operational, and cultural dimensions, the ontology offers a holistic framework that bridges previously siloed perspectives. Its structured approach to defining sub-dimensions, attributes, and their associated properties enhances the granularity and depth of readiness assessments, making it a pivotal reference point in the research landscape.

One critical implication is the interoperability this model introduces between disparate maturity and readiness frameworks. Existing models, such as IMPULS, SIRI, and Acatech, often emphasize specific aspects of readiness, such as technology deployment, organizational strategy, or workforce skills. The proposed ontology synthesizes these elements, offering a unified structure that incorporates strategic foresight, leadership commitment, digital infrastructure, process optimization, workforce competency, and cultural readiness. This integration ensures that no key dimension is overlooked, enabling researchers to analyze Industry 4.0 readiness through a comprehensive lens. Moreover, the ontology's inclusion of properties and cardinalities facilitates interoperability between different domains of analysis. For instance, relationships such as aggregates, hasCriteria, and isEvaluatedUsing allow researchers to map criteria and indicators across dimensions, enabling comparative studies between industries or geographic regions. This ability to establish linkages between criteria across strategic, technological, operational, and cultural domains helps advance the theoretical foundation for multi-dimensional readiness studies.

The ontology also advances the understanding of interdependencies between dimensions. For example, the cultural dimension's attributes, such as readinessLevel and changeResistance, are intrinsically linked to strategic and operational dimensions, such as leadership engagement and process standardization. By explicitly modeling these interdependencies, the ontology highlights the cascading effects of progress or bottlenecks in one dimension on others, offering new insights into the dynamic nature of Industry 4.0 readiness. In addition, the ontology introduces a functional perspective, with defined methods (e.g., evaluateProgress(), analyzeSkillGap (), and generateInsights()) that provide a basis for operationalizing readiness assessment. This functional view enables researchers to explore not only static maturity levels but also dynamic transitions and improvement trajectories, which are often missing from traditional models. This theoretical shift aligns with the ongoing need in the research landscape to transition from static assessments to continuous, iterative improvement frameworks. The ontology emphasizes also the scalability and adaptability of readiness models. By accommodating both single-value attributes (e.g., readiness Level) and multi-value attributes (e.g., trainingPrograms or partnerships), it ensures flexibility for application across industries of varying sizes and complexities. This adaptability addresses a significant gap in existing research, where models are often criticized for being too rigid or industry-specific.

B. Practical Applications in Industry 4.0 Maturity Assessment: Bridging to Industry 5.0 Readiness

The conceptual model of the Industry 4.0 readiness ontology, presented in Fig. 4, extends its theoretical robustness to practical applications in assessing Industry 4.0 maturity while paving the way for Industry 5.0 readiness. By capturing essential dimensions such as strategy, technology, operations, and culture, the model equips organizations with a structured and actionable framework to evaluate their current capabilities and chart a clear path toward technological and organizational evolution.

The ontology's multi-dimensional structure allows organizations to conduct a detailed maturity assessment, evaluating their performance across strategic, technological, operational, and cultural dimensions. For example, companies can assess their digital infrastructure and automation capabilities under the technological dimension while simultaneously evaluating leadership commitment and workforce skills under strategic and operational dimensions. This holistic approach ensures that organizations not only implement technology but also align it with strategy and culture, avoiding common pitfalls of fragmented adoption. By using properties such as analyzeSkillGap(), organizations can identify specific areas of improvement. The ontology's capability to aggregate multiple dimensions ensures that assessments are not isolated but interlinked, highlighting interdependencies that can accelerate or hinder progress. For instance, a lack of investment in leadership engagement may directly impact the success of cultural transformation initiatives. The scalability of the ontology makes it adaptable to various industries and business sizes. For large-scale manufacturers, the model can evaluate complex systems like real-time data access, IoT network integration, and robotic automation. Meanwhile, for small and medium-sized enterprises (SMEs), the focus can shift to incremental improvements, such as standardization of processes and upskilling the workforce. This flexibility ensures the model's relevance across the industrial spectrum, addressing both high-tech innovators and businesses in the early stages of transformation.

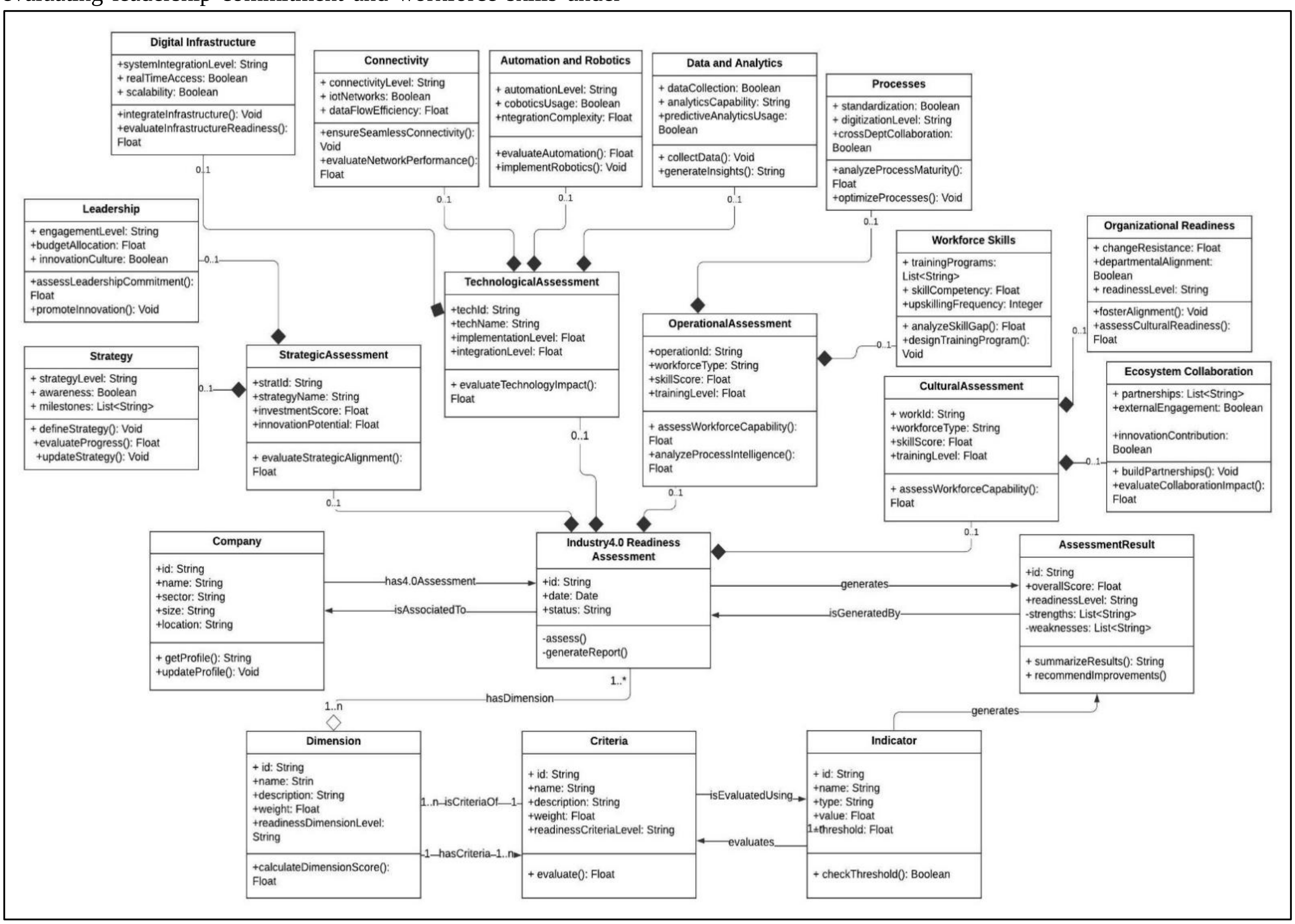

Fig. 4. Industry 4.0 Assessment conceptual model.

While rooted in Industry 4.0 principles, the ontology lays the groundwork for Industry 5.0 readiness by emphasizing human-centric innovation and sustainability. For instance, dimensions like workforce skills and cultural readiness align with Industry 5.0's focus on human-machine collaboration, where the role of cobotics and innovation culture becomes increasingly significant. The ontology's inclusion of attributes such as coboticsUsage, changeResistance, and trainingPrograms allows organizations to assess and enhance their preparedness for the collaborative, human-centered environments that define Industry 5.0. Furthermore, the ecosystem collaboration sub-dimension promotes partnerships and external engagements that are critical for sustainability and co-innovation in Industry 5.0. Functions like buildPartnerships() and evaluate Collaboration Impact() enable organizations to strengthen their position within an interconnected industrial ecosystem, fostering resilience and adaptability. The functional perspective embedded in the ontology supports real-time monitoring and continuous improvement. Methods such as evaluateProgress() and generateInsights() provide organizations with tools to regularly assess their Industry 4.0 maturity levels and dynamically adapt their strategies. This iterative approach ensures that organizations are not only maintaining their Industry 4.0 capabilities but are also actively transitioning toward Industry 5.0 readiness. The ontology facilitates benchmarking by enabling comparisons across industries, regions, and organizational sizes. Organizations can use indicators and criteria modeled in the ontology to measure their progress against industry standards or peers. This capability aids in identifying competitive gaps and aligning strategic decisions with industry trends.

For instance, companies can leverage insights derived from evaluateAutomation() and assessLeadershipCommitment() to prioritize investments and allocate resources more effectively. The ontology provides then a roadmap for organizations to future-proof their operations. By incorporating both current Industry 4.0 requirements and emerging Industry 5.0 principles, the model ensures that businesses are prepared for evolving technological landscapes. Attributes like scalability, predictiveAnalyticsUsage, and innovationCulture allow organizations to anticipate and adapt to future challenges, ensuring long-term competitiveness and sustainability.

The practical applications of the Industry 4.0 readiness ontology extend beyond assessing maturity. By offering a comprehensive, adaptable, and future-oriented framework, the model empowers organizations to not only excel in Industry 4.0 adoption but also position themselves as leaders in the transition to Industry 5.0. Its focus on interoperability, human-centric innovation, and continuous improvement makes it an essential tool for driving industrial transformation in an increasingly complex and interconnected world.

V. Conclusion

In conclusion, this research has developed a comprehensive conceptual model for assessing Industry 4.0 readiness and maturity, encapsulating the multifaceted dimensions and interrelationships critical to successful digital transformation. By integrating principles from prominent methodologies and drawing inspiration from established frameworks like IMPULS, SIRI, and Acatech, the proposed ontology provides a structured and holistic perspective on readiness assessment. The model delineates key connections between strategic, technological, operational, and cultural dimensions, offering insights into leadership engagement, digital infrastructure, workforce skills, and organizational alignment. Through its robust structure of classes, relationships, and functional properties, the ontology facilitates a nuanced understanding of interdependencies, enabling organizations to evaluate their maturity comprehensively and identify areas for improvement.

The conceptual model also establishes a foundation for bridging Industry 4.0 and Industry 5.0 readiness, emphasizing human-centric innovation, sustainability, and collaborative ecosystems. By accommodating diverse organizational contexts and fostering interoperability between dimensions, the model addresses critical gaps in existing frameworks, providing a flexible tool for continuous improvement and strategic decision-making. This work thus contributes to advancing the theoretical and practical landscape of Industry 4.0 readiness assessments, serving as a valuable resource for researchers, practitioners, and policymakers navigating the complexities of digital transformation.

The next critical step is to leverage this conceptual model to develop a fully operational ontology for Industry 4.0 readiness and maturity assessment. Such an ontology would formalize the domain knowledge, enable standardized representation, and enhance interoperability across systems, ultimately supporting tools for benchmarking, diagnostics, and strategic planning. By transitioning from conceptual modeling to ontology implementation, this work can catalyze meaningful progress in industrial transformation, positioning organizations to thrive in the evolving landscapes of Industry 4.0 and beyond.

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