Modular Ontology to Support Manufacturing SMEs Toward Industry 4.0

Zaida Antonieta Mora-Alvarez
CIATEQ A.C., Centro de Tecnología Avanzada, Mexico
zaidamoraalvarez@gmail.com

Óscar Hernandez-Uribe
CIATEQ A.C., Centro de Tecnología Avanzada, Mexico
oscar.hernandez@ciateq.mx (corresponding author)

Ramon Alberto Luque-Morales
CIATEQ A.C., Centro de Tecnología Avanzada, Mexico | Department of Industrial Engineering, Universidad de Sonora, Mexico
ramon.luque@unison.mx

Leonor Adriana Cardenas-Robledo
CIATEQ A.C., Centro de Tecnología Avanzada, Mexico
leonor.cardenas@ciateq.mx

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ABSTRACT

Industry 4.0 (I4.0) implementation is a hot topic among manufacturing organizations to reach smart factory status and integrate a fully connected ecosystem. Achieving such a transition presents notable challenges for Small and Medium Enterprises (SMEs) since they often face resource and skilled personnel limitations. This study developed a domain ontology to represent various stages of maturity toward I4.0 implementation. Ontology provides a tool for SMEs to self-assess in situations of machines, processes, and factories for the dimensions of control, integration, and intelligence. This study focused on the identification of classes and relationships according to I4.0 implementation situations in the context of a manufacturing setting, the reuse of ontologies related to the domain of observations to model situations, and the creation and validation of the ontology through the information obtained from the questionnaires applied to SMEs. Finally, the ontology delivers a tool to understand SMEs' current state concerning I4.0 implementation and plan based on informed decisions about the maturity state and the technology required to advance to the next stage in their manufacturing processes.

Keywords-domain ontology; industry 4.0; SMEs; smart factory; SPARQL; semantic web

I. INTRODUCTION

The manufacturing industry has undergone profound changes due to the influence of new technologies, increasing the complexity of knowledge and information [1]. Innovation and technological development have accelerated the transformation of manufacturing processes, making them progressively complicated, automatic, and sustainable [2-3]. On the other hand, globalization and company relocation have generated challenges such as competition in the global market, greater flexibility and efficiency in processes, personalized products and services, and shorter innovation cycles [4-5]. These issues have been addressed by the Smart Factory (SF) or Factory of the Future (FoF) in the context of Industry 4.0 (I4.0) [6].

I4.0 is characterized by horizontal, vertical, and end-to-end integration, enabling the connection between machines and humans through the Internet of Things (IoT) and cyber-physical systems [7-8]. The I4.0 strategy promotes significant advantages in manufacturing value chain, product, and service innovation, relying on advances in information, communication, automation, and intelligence technologies [9-10]. On the other hand, I4.0 implementation in Small and Medium Enterprises (SMEs) is a complex transition influenced by different drivers and barriers [11-12]. It implies a general digital transformation and challenges compared to large or multinational companies concerning financial resource constraints, technology awareness, and knowledge [13, 14]. SMEs adopt different strategies to achieve digital transformation, for example, the SF or FoF paradigms, driven by the inclusion of disruptive technologies and influenced by economic, social, and organizational dimensions [13-16]. The path to be followed by SMEs must be planned and executed gradually through progressive stages to synchronize all processes and areas to ensure the profitability and socio-environmental benefits expected from this transformation [17].

Two approaches prevail for context handling in smart environments: data-driven (e.g. machine learning methods) and knowledge-driven (e.g. ontology-based) [18]. In this sense, "an ontology is a formal, explicit specification of a shared conceptualization" [19-20]. It enables clarifying the meaning of terms in specific contexts and establishing machine-understandable standards [21]. The interest in ontologies and semantic web technologies within the manufacturing field has increased, supported by the adaptation, collaboration, interoperability, cloud services, and automation of I4.0 [22-23]. Diverse frameworks, maturity or readiness models [24-27], and roadmaps [28-29] have been developed to guide the adoption of I4.0 in companies. Maturity and readiness models usually contemplate levels, dimensions, and descriptors or Key Performance Indicators (KPIs) to evaluate conditions or states based on the premise that people, organizations, and processes evolve to maturity through different levels using a measuring scale [17, 30]. Levels represent stages of maturity, whereas dimensions specific capabilities of the I4.0 implementation domain [31-32]. The IMPULS model is commonly used to assess the maturity and readiness of organizations and measures six dimensions: strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees [33]. In [34], this model was used in a steel manufacturing company, while in [35], it was applied to understand and characterize SMEs in Malaysia. Concerning frameworks, the reference architecture model for I4.0 (RAMI 4.0) includes the IT elements and components in a layered and life-cycle model, and the hierarchy levels represent the different functionalities within factories [36]. Another hierarchical framework was proposed in [37] to serve as a roadmap for SMEs to implement I4.0, based on two levels with three types: intelligence (control, integration, and intelligence) and automation (machine, process, and factory), generating a total of nine applications [37].

In the era of the IoT, machines, sensors, and assets communicate with each other, becoming context-aware and providing added value. According to [18], context is any information used to characterize the situation of an entity, while context data constantly change and can be highly heterogeneous. Context awareness provides services by examining the user's context to assist workers in decision-making and boost their activities, improving factory performance [38-39]. Thus, situation awareness refers to the continuous extraction of environmental information to be integrated with previous knowledge, updating the system in a real-world environment [40]. In [41], it was used in IoT applications, defining classes and properties to exchange data using the Semantic Sensor Network (SSN) ontology [41].

There is no consensus on the dimensions considered in the frameworks or maturity models, while there is a lack of clarity in the constructs of maturity levels and inflexibility in their application, and they do not fully cover all the specific needs of SMEs [9, 31, 42]. Furthermore, there are not enough case studies and success stories to guide implementation within SMEs, and they are not standardized and depend on the initial conditions, characteristics, and culture of organizations [16]. Moreover, the roadmap to I4.0 using an ontology-based approach remains limited due to the high cost of developing ontologies, development issues, and finding trained human resources. This gap hinders the fulfillment of the reusability of data, metadata, and processes [43]. This study addressed the development of a domain ontology in I4.0 based on a framework to support the implementation stages of SM in SMEs. The aim was to contribute with an ontology to model the situation of maturity levels of SMEs and determine their state of readiness on their way to I4.0.

II. METHODOLOGY

The roadmap for a digital transformation strategy toward I4.0 requires organizations to identify their current situation (e.g. machines or processes in a control or integration dimension). With this in mind, this work presents an ontology proposal for manufacturing SMEs' transition to I4.0 (OMSTI4), which aims to capture general notions of the state or situation of companies concerning preparation and stages of progress toward I4.0 implementation. The OMSTI4 represents the situations of the resources in manufacturing settings (e.g. machines or processes) based on the categorical framework presented in [37] that corresponds to the dimensions of control, integration, and intelligence related to its supply chain. Moreover, OMSTI4 models such situations identified by SMEs (e.g. regarding technology and production processes), with elements of the framework proposed in [44]. Figure 1 presents a conceptual model of OMSTI4, where stages and situations are connected to show a perspective of the current state of the factory maturity level as a function of stakeholders, observations, dimensions (e.g. control or integration versus machine or process), and the collected facts.

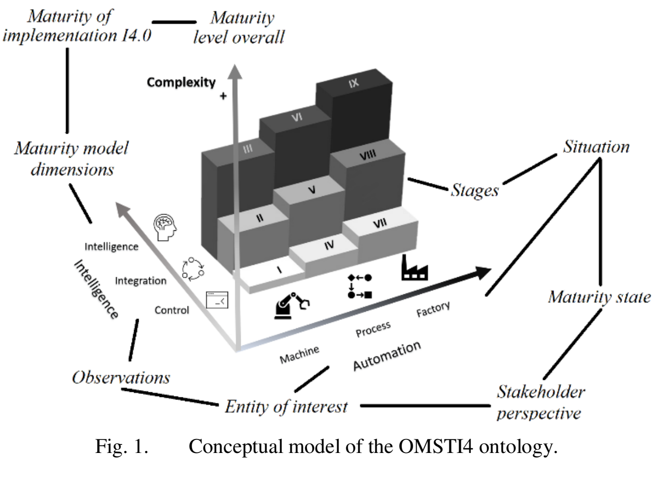

Fig. 1. Conceptual model of the OMSTI4 ontology.

The implementation of OMSTI4 used the ontology development 101 guide [45], the modular ontology modeling methodology, and the reuse of ontology design patterns [46]. The definition of classes and semantic relationships employed

OWL language [47], relying for their construction on the Protégé 5.6.1 tool [48] and the Cellfie plugin [49]. In compliance with the requirements and to validate the ontology [50], a sample of Competency Questions (CQ) was presented:

- CQ1: What is the maturity level of an SME in each of the nine stages of the OMSTI4 model?
- CQ2: What is the maturity level of an SME identified in the dimensions of machine, process, and factory?
- CQ3: What is the maturity level of an SME identified in the dimensions of control, integration, and intelligence?
- CQ4: What is the overall maturity level of an SME regarding the implementation of I4.0?
- CQ5: What other data related to SME self-assessment is available?

The key concepts included in the classes for OMSTI4 implementation are situation, stages, maturity state, I4.0 maturity model, dimension, subdimension, and maturity level, with several links among them. For instance, the situation class is central to the proposed ontology to model the state of the maturity level toward I4.0 implementation for an SME through observations of the entity of interest, according to the automation level (machine, process, and factory) on the intelligence level (control, integration, and intelligence). The situation class represented by the SME profile information and the set of observations of the average implementation maturity level correspond to the SMEs' responses from the questionnaires based on IMPULS [33] and 3D-CUBE [30].

The stage class comprises characteristics according to the design principles of I4.0 of interoperability and consciousness. The first refers to the sub-dimensions: digitalization, communication, standardization, flexibility, real-time responsibility, and customizability, while the second deals with predictive maintenance, decision-making, self-optimization, and self-configuration. The stakeholder concept is assimilated according to the ISO standards [51-52], resulting in the stakeholder perspective class that supports the representation in the OMSTI4 for the machine, process, and factory entities (subclasses of entity of interest), which are the dimensions that represent the observations toward I4.0. The observed property of maturity of the implementation of I4.0 in a company is measured using a scale based on IMPULS, from 0 to 5 (outsider, beginner, intermediate, experienced, expert, and top performer), and analyzed in concordance with the dimensions of control, integration, and intelligence. The context ontology presented in [18, 53] reuses core ontologies to build a modular ontology of the manufacturing domain. Thus, it is suitable to adapt and represent the intended context in the OMSTI4 for the machine, process, and the relationships of the situation, observation, resources, feature of interest, sensor, and observable property. Figure 2 shows a subset of classes that identifies the key concepts above, the object properties, and the data properties to analyze the different dimensions of the maturity implementation of I4.0. Furthermore, Table I shows a module that contains a subset of classes registered in Wikidata [54].

TABLE I. A SUBSET OF CLASSES OF OMSTI4.

Class	Description
Implementation of I4.0 (Q117354032)	Implementation or execution of the plans, roadmaps, procedures, and others, for an entity to reach the change or transition from its current state toward I4.0.
CFI4.0_Stage1 (Q114682905)	This stage considers two dimensions: machine and control.
CFI4.0_Stage5 (Q114692253)	This stage considers two dimensions: process and integration.
CFI4.0_Stage9 (Q114693131)	This stage considers two dimensions: factory and intelligence.
Maturity Model (Q121402594)	A conceptual model that consists of a sequence of discrete maturity levels for processes in one or more business domains and represents a desired or expected evolutionary path.

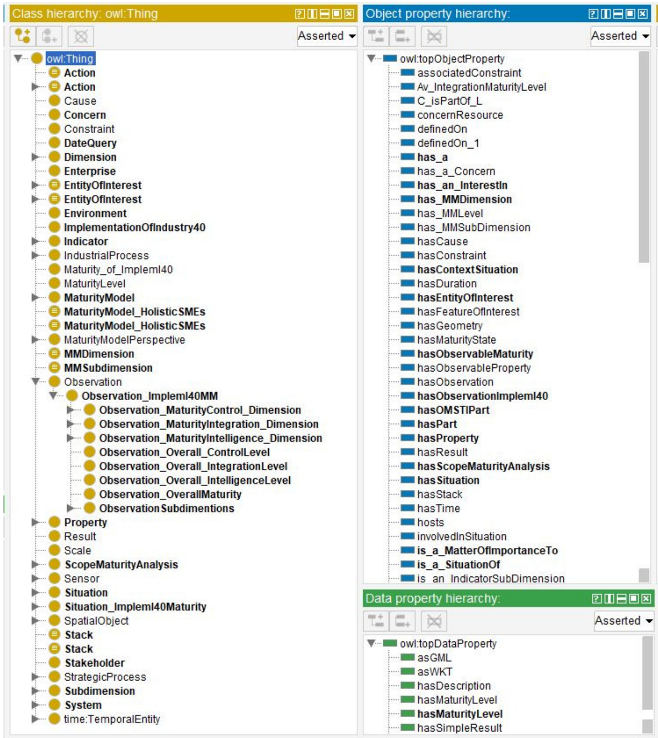

Fig. 2. OMSTI4 general class hierarchy view.

III. RESULTS AND DISCUSSION

Based on questionnaires applied to SMEs to assess their maturity in I4.0 implementation, the proposed ontology was populated to perform queries and to evaluate dimension, stage, and overall maturity level. Figure 3 depicts a visual perspective of the developed ontology, comprising classes, subclasses, and their relationships. As a result of the implementation of OMSTI4, Figure 4 illustrates a *Protégé* window with individuals, types, and properties. The Pellet reasoning plugin was applied to the OMSTI4 ontology, returning a consistent ontology model. For instance, *Dimension_Intelligence* has some object properties assertions such as *isPartOf* related to *Stack_ProductionProcesses* and *is_a_MMDimensionOf* related to CFI40. The reasoner detects that the individual is a type of *MMDimension* since there is an explicit object property assertion named *is_a_MMSubDimensionOf*.

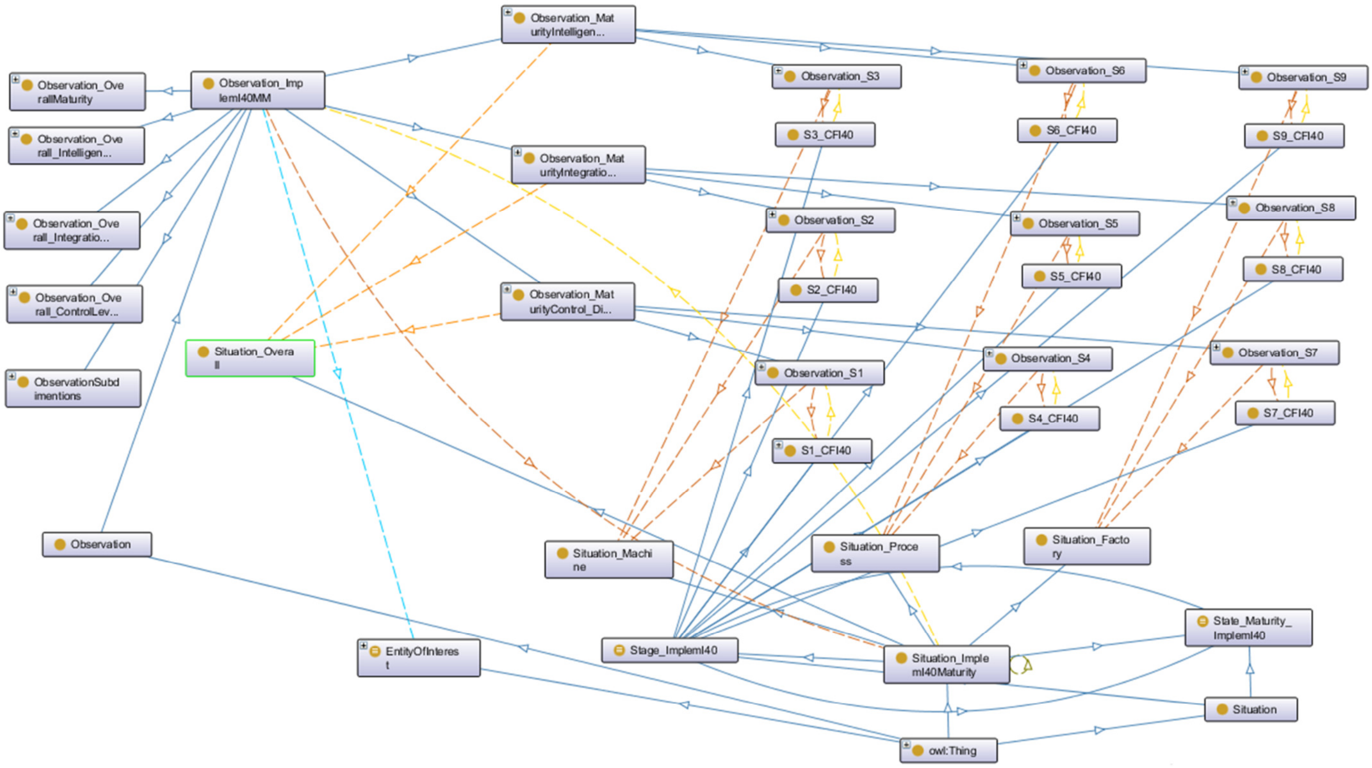

Fig. 3. A partial visualization of OMSTI4 classes and relations.

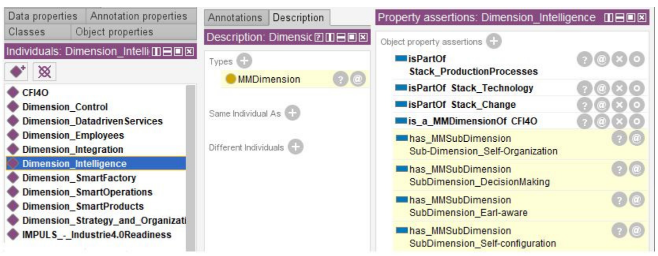

Fig. 4. Inference visualization for the individual *Dimension_Intelligence*.

The object property *is_a_MMSubDimensionOf* links the sub-dimensions classes (self-organization, decision-making, early-aware, self-configuration) with *Dimension_Intelligence*, and the range of the object property *is_a_MMSubDimensionOf* connects to the class *MMDimension*. Regarding the object properties inferences, for instance, *has_MMSubDimension* is reasoned due to its inverse property *is_a_MMSubDimensionOf*.

Figure 5 depicts the results of CQ1, where the column *ObservationsMatEnt* addresses the observations of the entity of interest according to the grade of automation in the dimension machine, process, and factory, and on the intelligence level in the dimension of control, integration, and intelligence through the column *ObservablePropert*, showing the maturity level of an SME in each of the nine stages in the column *sosaResult*. For instance, in the fourth row, the individual *cfi4:Observ_ENT_1_DC_P* indicates the dimension of process and control by the *ObservablePropert*, revealing stage IV with a maturity level of 4.

Figure 6 shows the results of CQ3 and CQ4, where the first row displays the overall maturity level of an SME, *cfi4:Observ_ENT_1_Overall*, with a maturity level of 2.67 in column *ML*. The following three rows address the maturity level per integration, intelligence, and control dimension with values Level_3_Experienced, Level_2_Intermediate, and Level_3_Experienced.

Several research efforts have been conducted in frameworks or maturity models regarding knowledge representation and modeling with ontologies to support the transition to I.4.0 in business. However, there are still open topics for research due to the nature of its requirements (e.g. resources, systems, and processes, among others) [55]. For instance, in [56], a maturity model was proposed for construction companies, using I4.0 models to measure the organizational aspects and provide a guideline for developing a business strategy. In [57], a knowledge graph was proposed for I4.0 related to standards, norms, and reference frameworks, providing a linked data-conform collection of annotated and classified reference guidelines to support users in understanding how to implement I4.0 systems. In [58], an ontology-based model was presented for digital transformation knowledge, adaptable to any sector for a digital strategy in a company. In [59], a knowledge graph was built, identifying core concepts of I.4.0 and introducing a reference ontological model focused on production lines. In [60], an ontology for the asset administration shell of RAMI4.0 was proposed as an extensible basis for information systems to enhance the interoperability of assets from different manufacturers. These works, OMSTI included, share the use of ontologies as tools to structure and represent knowledge related to technology, organizational maturity, and knowledge management for I4.0 implementation. Table II shows the criteria to identify similarities among them.

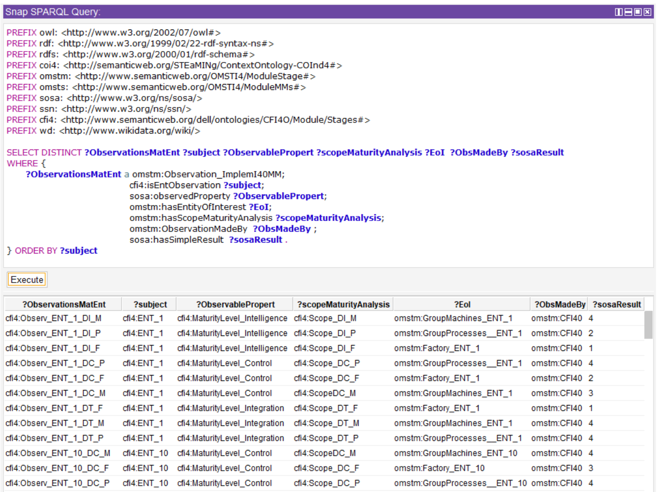

Fig. 5. The maturity level of an SME for each of the nine stages.

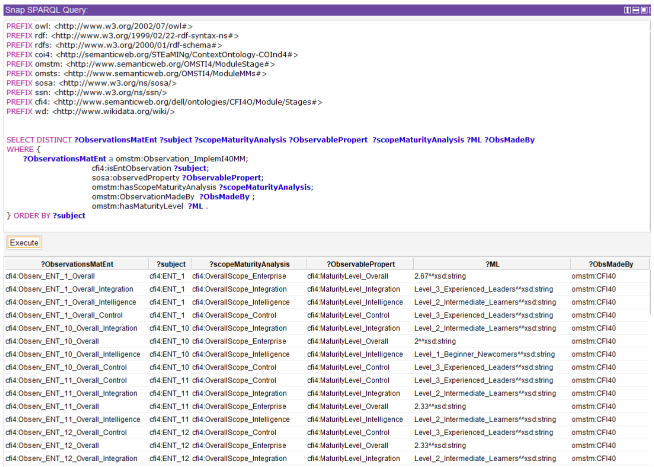

Fig. 6. Dimension (control, integration, and intelligence) and overall maturity levels.

The primary criteria considered in this research were the development state, dimensions of the model, models, frameworks, and standards embraced in ontology creation to support I4.0 implementation. Technology and production process were the commonly used dimensions, whereas organization and change were also considered. As a foundation to create the ontological model, most research works used the RAMI 4.0 and industrial standards, although others employed the Building Information Model (BIM). Furthermore, the most well-known ontologies used by the reviewed works were Dolce Ultralite, SSN, ontology of measurements, and BIM.

The reviewed studies focused their efforts on companies in general, regardless of their size, while manufacturing SMEs face digital transformation challenges and resource constraints to achieve I4.0. Therefore, more studies will further help to bridge this research gap. This study focused on manufacturing SMEs and employed well-known questionnaires to populate the ontology (i.e. IMPULS and 3D-CUBE) through the stakeholders' perspective. It incorporated the context to establish a situational state of machines, processes, and factories to support SMEs toward I4.0 adoption.

TABLE II. COMPARISON BETWEEN OMSTI4 AND RELATED WORKS

Criteria	[56]	[57]	[58]	[59]	[60]	OMSTI4
Development	ont	ont	onm	onm	ont	ont
Dimensions [44]	t; pp; o; ch	t; pp; o	t; pp; p; o; ch	t; pp; o; ch	t	t; pp
Models/frame-works/standards	mm;b	r; i4; ot	b	r	r	mm; i4; r;
Competency questions	-	yes	-	-	yes	yes
Reusing ontologies	-	yes	yes	yes	-	yes
Questionnaire or DB to populate	yes	-	-	-	-	yes
Evaluation [50]	a	c	-	v	c	q

Development: ont=ontology, onm=ontology model.

Dimensions: t=technology, pp=production processes, o=organization, ch=change, p=people.

Models/frameworks: mm=maturity or readiness model of I4.0, r=RAMI 4.0, b=building information model, i4=ISO-42010, ot=others standards.

Evaluation: *Evaluation of ontologies*: q=competency questions, v=verification, c=evaluation by criteria. *Validation of ontologies*: a= application-based, u= user-based. "-"=not mentioned.

IV. CONCLUSION

This article proposed and developed a modular ontology to support manufacturing SMEs to assess the maturity level in their efforts to implement I4.0. OMSTI4 provides the means for SMEs to identify their maturity state for the intelligence level according to the dimensions of control, integration, and intelligence, and automation level in machine, process, and factory dimensions. OMSTI4 can serve as a knowledge base for industry and researchers interested in exploring the current state of the domestic factory maturity level. Furthermore, it allows SMEs to make more informed decisions and advance their path toward digitalization and industrial automation, laying the foundation for business collaboration and developing valuable support strategies.

OMSTI4 offers SMEs a valuable tool to evaluate and know their current state toward I4.0, contributing with a snapshot of the overall advancement of the company and encouraging innovation in this challenging field. Furthermore, this study sets the groundwork from an SME perspective by collecting data using questionnaires to build a valuable knowledge base using ontologies and address the I4.0 transformation of SMEs in México. Future work will consider the creation of software that incorporates the core of OMSTI4 after the enhancements of the ontology through validations based on the criteria of experts in the knowledge domain of engineering and I4.0, with the intention of promoting collaboration between SMEs and integration of their supply chains.

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AUTHOR PROFILES

Zaida Antonieta Mora-Alvarez is a Ph.D. candidate in the program of Advanced Manufacturing, Posgrado CIATEQ, A.C. She obtained a M.Sc. degree in Engineering with a specialization in Quality Systems and Productivity from Tecnológico de Monterrey (ITESM). Her research and teaching interests include the theory and application of production processes, manufacturing systems, supply chains, and knowledge discovery.

Óscar Hernández-Uribe is a researcher at the Centro de Tecnología Avanzada (CIATEQ), Mexico. He holds a Ph.D. in Systems and Automation. His research focuses on extended reality, deep and machine learning, ontologies, and semantic web technologies for the health, water, and energy sectors. He is a member of the National Research System (SNI) of Mexico.

Ramón Alberto Luque-Morales is a Ph.D. candidate in the program of Advanced Manufacturing, Posgrado CIATEQ, A.C. He holds a M.Sc. degree in Industrial Engineering. Since 2013, he works as a full-time Associate Professor at the University of Sonora.

Leonor Adriana Cárdenas-Robledo is a researcher at the Centro de Tecnología Avanzada (CIATEQ), Mexico. She holds an M. Sc. in Computer Science and a Ph.D. in System Engineering. Her research focuses on ubiquitous learning, virtual and augmented reality, and technology-enhanced learning. She is a member of the National Research System (SNI) of Mexico, Level I.