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Ontology-based knowledge representation of industrial production workflow

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ABSTRACT

Industry 4.0 is helping to unleash a new age of digitalization across industries, leading to a data-driven, interoperable, and decentralized production process. To achieve this major transformation, one of the main requirements is to achieve interoperability across various systems and multiple devices. Ontologies have been used in numerous industrial projects to tackle the interoperability challenge in digital manufacturing. However, there is currently no semantic model in the literature that can be used to represent the industrial production workflow comprehensively while also integrating digitalized information from a variety of systems and contexts.

To fill this gap, this paper proposed industrial production workflow ontologies (InPro) for formalizing and integrating production process information. We implemented the 5 M model (manpower, machine, material, method, and measurement) for InPro partitioning and module extraction. The InPro comprises seven main domain ontology modules including Entities, Agents, Machines, Materials, Methods, Measurements, and Production Processes. The Machines ontology module was developed leveraging the OPC Unified Architecture (OPC UA) information model. The presented InPro ontology was further evaluated by a hybrid combination of approaches. Additionally, the InPro ontology was implemented with practical use cases to support production planning and failure analysis by retrieving relevant information via SPARQL queries. The validation results also demonstrated that using the proposed InPro ontology allows for efficiently formalizing, integrating, and retrieving information within the industrial production process context.

1. Introduction

The industries are currently engaging in the fourth industrial revolution by embracing digitalization and intelligentization [1]. Recently, global manufacturing industries have witnessed a considerable penetration of information technologies into all facets of the product life cycle. The integration between manufacturing systems and information and communication technologies (ICT), especially the Internet of Things (IoTs), has formed a new digital industrial era for industrial production [2]. This new industrial stage provides an opportunity for manufacturing industries to maintain more interconnected and smart factories where workers, machines, processes, and products interact to create a better comprehensive organization of all the product information, resulting in a higher level of efficiency and productivity [3]. Previous works have shown that the utilization of digital technologies leads to a reduction in set-up times, labor and material costs, and processing times, thus increasing the productivity of production processes [4,5].

Advanced ICT implementations enable high-efficiency data collection and low-latency data transmission between the corresponding entities in the production process. However, the heterogeneity and complexity of data sources and systems make it challenging to develop high-confidence, secure, and certifiable methodologies [6]. This is due to a dramatic increase in the amount, variety, and availability of data and information, resulting from an increasing number of interconnected physical objects and information systems [7]. Moreover, as manufacturing systems become more complicated and participating stakeholders, along with their associated software tools and legacy systems, become more diverse and heterogeneous, knowledge and data sources become increasingly fragmented, siloed, and disintegrated [8]. The information involved in the related entities is obtained by various industrial systems and software, namely, Enterprise resource planning (ERP), Product Life cycle Management (PLM), Manufacturing Execution

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Systems (MES), and so forth, developed by multiple vendors using different interfaces or protocols [9]. Since each of those applications has its own data models, distributed information cannot be transmitted autonomously among the various systems. Therefore, a strong demand for formalized and effective data infrastructure emerged [10]. Furthermore, with the growing number of systems and application programming interfaces (APIs), manual reprogramming becomes increasingly time-consuming and costly. Inadequate semantic integrity of data hampers efficient cooperation, communication, and decision-making during the production process [8]. Therefore, to provide a comprehensive picture of the production workflow, a systematic integration of all pertinent data from multiple systems and devices based on production domain knowledge should be explored. Such an interoperable integration in the smart factory can also be considered an essential feature to accomplish a production goal, taking care of efficiency and resource usage [3].

Ontology is an explicit specification of a conceptualization [11]. In other words, ontology is an approach that defines, captures, and standardizes information, and makes it explicitly available for sharing or reusing information, data, and domain knowledge [12]. Ontological knowledge representation enables a commitment to information integration from various information systems [13]. Both humans and computers can understand domain knowledge unambiguously based on such a commitment. Therefore, developing formalized knowledge representation is a promising solution to the interoperability challenge discussed above. Various scholars have contributed to the development of manufacturing ontologies over the years. However, most of the research efforts have focused on either establishing the core concept of manufacturing or utilizing ontologies in application systems [14]. A holistic ontology representing the industrial production workflow and integrating the digitized information from multiple industrial systems has not been developed to date in the manufacturing field.

This paper aims to address the aforementioned research gap by introducing an industrial production workflow ontology (InPro), which provides a conceptualization and formalization of the production workflow through shared and reused domain knowledge representation. The InPro is a clear, formalized information framework that facilitates the integration of knowledge and data from multiple software and systems, enabling a comprehensive overview of the production workflow. Additionally, the proposed ontology leverages semantic technologies for information retrieval and reasoning to support production process planning, management, and analysis. The InPro ontology can benefit relevant stakeholders working in manufacturing system integration, as it serves as a demonstration of how linked data frameworks can be used to integrate and utilize heterogeneous information.

The paper is structured as follows: Section 2 provides an overview of related work on the background knowledge of the production process, ontologies, and other semantic-based resources in the industrial production process. Section 3 presents the methodology for developing the proposed InPro. In Section 4, a comprehensive description of the InPro ontology is provided. Section 5 presents the evaluation of approaches and results, along with a case study demonstrating the use of the proposed InPro. This section is followed by a discussion in Section 6 on the research's contributions, limitations, and potential future research directions. Finally, the paper concludes with a summary of the study.

2. Related work

2.1. Production workflow and five main components (5 M)

The production process is a critical part of any business. It is defined as"the process followed in a plant for converting semi-finished products or raw materials into finished products or raw materials into finished products". [15]. The production process is dynamic, continuously analyzed, and tweaked to improve productivity. Lean Manufacturing is considered an efficient method to achieve desired output levels with minimal input resources, aiming to reduce transforming costs like labor, energy, and waste output [16]. Identifying parts of processes that add value is essential to optimize these processes and maximize their benefit.

Optimizing processes start with identifying the inputs and waste related to the production workflow. Researchers have proposed various ways of classifying inputs. The 4Ms (manpower, machines, materials, and methods) are considered essential to successful lean manufacturing, as they provide the basic stability necessary for general predictability and consistent availability [17]. Production systems can be improved by identifying and eliminating waste associated with these inputs [18]. To further systematically investigate the improvement of the production sites, Fansen [19] introduced the 5M1S1E approach, accounting for the areas of manpower, machinery, material, method, measurement, safety, and environment. In addition to those, from a project management perspective, 5 M refers to method, machine, material, measurement, and manpower. These factors can be analyzed to determine their root cause in case of failure [20]. Furthermore, Liliana [21] discussed 6 M, which includes materials, methods, man, machines, mother nature(environment), and measurement. These factors were used with the Ishikawa model for quality assessment in the machine construction field.

In summary, M-based models in the manufacturing domain can be designed based on different applications. In the context of production processes, safety is not a physical or tangible resource that is transformed or utilized. Instead, it refers to a set of practices and protocols that guarantee the protection and well-being of workers and the environment throughout the production process. While safety measures play a crucial role in preventing accidents, injuries, and environmental damage, they are not classified as input resources that are transformed into a product output. Additionally, the environment is viewed as a surrounding factor that could affect the production process, rather than a primary input of the production process. Hence, the 5 M model, representing the essentials required by the production process, is simplified into five key components: manpower, machine, material, method, and measurement. Fig. 1 shows the 5 M model for production workflow in this research. The following Section 3 illustrates the implementation of the 5 M model for the development of the InPro ontology.

2.2. Ontology works for the manufacturing domain

Various ontologies have been developed in the industrial manufacturing domain to provide formalized knowledge representation and support information integration. Several formal ontologies focus on basic conceptualization to cover the fundamental semantics of everything in the manufacturing domain. For example, the ADACOR [22] ontology was developed to establish the conceptual and formal foundations of manufacturing ontologies, describing products, manufacturing processes, resources, and the relations among them. Similarly, ontology MASON [23] provides core manufacturing concepts but does not consider relations and capabilities. The PSL ontology was developed to formalize process information within manufacturing systems. Suriati and Rafael [24] proposed manufacturing process

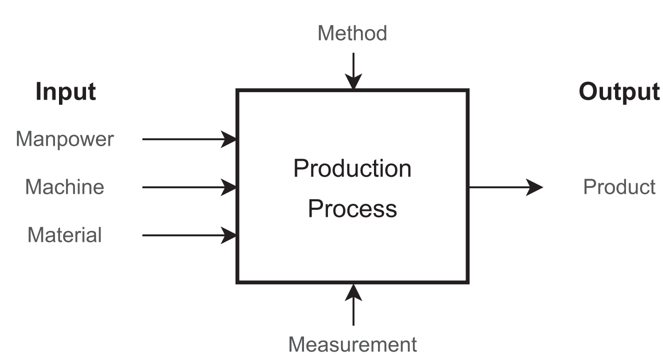


Fig. 1. 5 M model-based production workflow.

ontologies to represent typical machining processes, such as turning, drilling, and milling. However, these ontologies are too generic and broad in scope for interoperability across specialized domains, as they may refer to various concepts like material, human, tool, gripper, mover, and so forth, under the concept 'Resource.' To address this issue, Zahid et al. [25] proposed a formal manufacturing reference ontology (MRO) that focuses on the production domain and partially on the design domain. The authors mainly concentrated on product design and identified the need for reference ontologies in the assembly domain rather than the production workflow. In addition, the standard form of product and process information models enables seamless data exchange among distributed information systems. OntoSTEP [26] transformed the STEP standard into an ontology, providing an ontology to STEP schema and its instances in an OWL format. Pannetto et al. [27] introduced ONTO-PDM to match product-related knowledge with standardization initiatives (ISO and IEC) to facilitate systems interoperability in a manufacturing environment.

In addition to the previously mentioned works, there are several ontologies in the manufacturing domain that are related to practical applications. For instance: Niklas et al. [28] provided an application-driven factory ontology for monitoring and automating factories. Cheng et al. [29] developed a manufacturing ontology based on Industry 4.0 demonstration production line. A computational ontology has been presented in [30] for representing and reasoning over additive manufacturing knowledge and data. OPW [31] is a low-level ontology-based digital twin for offsite manufacturing production workflow, focusing on representing the knowledge of the manufacturing aspect of the building life cycle from a BIM (building information modeling) worldview. Qin et al. [32] presented an ontological-based similarity retrieval application for heterogeneous 3D CAD models. However, it's worth noting that these ontologies are limited to specific scopes within the manufacturing domain and, as a result, cannot provide a holistic modeling of the production workflow.

To improve compatibility and standardization in the digital manufacturing domain, the Industrial Ontology Foundry (IOF) was established. The IOF aims to provide a suite of open and principles-based Reference Ontologies (RO) that cover the entire domain of digital manufacturing [33]. However, due to the vastness of the IOF project, it has been recommended that the IOF ontologies should be extended to specific subdomains and relevant applications [34]. It is yet to be determined whether the IOF will be successful in providing robust and reliable ontologies for manufacturing businesses. Nevertheless, it remains the most ambitious and noteworthy effort in this area to date [14]. Thus, to our knowledge, there is a lack of an ontology that could adequately represent the production workflow as well as integrate the digitalized information from various industrial information software and systems in the manufacturing domain.

2.3. Non-ontological semantic resource - OPC Unified Architecture (OPCUA) information model

In addition to ontological work in the manufacturing domain, there are already existing semantic resources that have been widely employed. The three-dimensional Reference Architecture Model of Industry 4.0 (RAMI 4.0) was proposed by the Plattform Industrie to create a common understanding of Industry 4.0 concepts for all associated stakeholders [35]. One of the core ideas of RAMI 4.0 is semantic information modeling [36], which requires standard technologies to ensure cross-vendor data exchange. In this context, OPC UA (IEC 62541) fits perfectly inside the RAMI 4.0 model [37]. OPC UA is a middleware communication protocol developed by the OPC Foundation for industrial communication, which also provides a semantic information space with extendable information models. The aim of OPC UA is to improve interoperability on the transport and semantic layer in typical IoT scenarios [38].

Semantic interoperability is mainly achieved by the graph-based OPC UA information model combined with Companion Specifications [38]. The OPC UA information model is organized by nodes and references, which enhances the data semantics. Companion Specifications [39], derived from OPC UA Base Information Models and based on the OPC UA Data Model, are often referred to as"Industry standard models" because they address specific industry problems. They help ensure a dedicated and consistent understanding of data across different systems. To support the creation of Companion Specifications, the OPC Foundation has developed various guidelines and templates, improving semantic interoperability. However, the OPC UA information models still lack formal semantics for automated data interpretation, which can be provided and enriched by ontologies and the related Semantic Web languages [40]. Applying ontologies in this context could enable information retrieval functions that would be beneficial to machine operators without extensive knowledge of OPC UA or automation. Several academic approaches have been proposed to convert OPC UA information models into domain-specific ontologies [41,42].

Currently, OPC UA Companion Specifications primarily focus on integrating existing and legacy equipment between different automation systems. In response to this, the VDMA [43], the largest manufacturing association in Europe, has released OPC UA Companion Specifications for Robotics and Machine Vision. However, there is still a lack of an information model for representing production workflows. In this paper, the focus was on developing the machine module ontology based on the OPC UA Companion Specifications OPC 40010-1 Robotics [44]. The purpose of this development was to ensure formalization and standardization in the representation of machine modules.

2.4. Other related ontologies works

In the review of ontologies outside the manufacturing domain, it was found that although these ontologies are not directly related to the production workflow, they provide top-level conceptualization or common terminologies that can be reused or linked with the InPro. Reusing existing ontologies offers benefits such as improving the reliability of ontology development and avoiding redundant modeling of overlapped concepts [45]. One such top-level ontology reviewed was the Basic Formal Ontology (BFO) [46]. BFO is a domain-neutral ontology designed for use in scientific and other domains, and it has been published as an ISO standard: ISO/IEC 21838-2 [47]. By mapping BFO with ontologies specific to the manufacturing domain, a clear knowledge representation can be achieved. Additionally, the OWL-TIME [48] ontology, which provides a representation of temporal concepts, can be used to describe temporal properties of resources in the production workflow.

In addition to domain ontologies from the manufacturing domain, the review also included domain ontologies from other domains to provide a representation of related entities. The Building Topology Ontology (BOT) [49] is a minimal ontology that allows for the description of core topological concepts in a building. The Information Artifact Ontology (IAO) [50] is an ontology of information entities that aims to define what constitutes an information entity. Finally, Digital Construction Ontologies (DiCon) [51] are used to enable semantic interoperability between systems in the construction and renovation domain. The context model in the DiCon allows the representation of multi-context information at the metadata level.

2.5. Research motivation

Industrial systems and information integration play a vital role in helping companies streamline and simplify their production processes, improve departmental communication and collaboration, enhance productivity, and enable real-time monitoring and management of operations in real-time for effective decision-making. However, achieving such integration is challenging due to the heterogeneity of information, with data collected from various sources under multiple contexts. To address this challenge, one of the solutions is to obtain a comprehensive knowledge representation of the industrial production process through systematic integration of information. Therefore, the aim of this paper is to provide an ontology-based knowledge representation for the production workflow.

3. Methodology

Ontology development requires adherence to specific methodologies to ensure that the developed ontology fulfills its intended goals. Some commonly used approaches include **ONTOLOGIES** [52], **METHONTOLOGY** [53], and **SKEM** [54]. These methodologies typically follow an iterative Waterfall feedback approach [55], which can be divided into four main parts: (1) Specification, which defines the scope, purpose, and domain of an ontology; (2) Knowledge Acquisition and Conceptualization, which reviews the domain knowledge and reuses existing resources; (3) Implementation, which constructs ontologies; (4) Evaluation. In contrast, **SAMOD** [56] and **AMOD** [57] adopt agile principles [58] and practices in the ontology development. This approach aims to reduce the complexity of ontology development activities and improve cooperation between ontology engineers and domain experts. Furthermore, many scholars have established their own ontology development approach by taking the main features of the approaches into account [51,59].

The increased size of ontologies can indeed lead to various challenges at different stages of the ontology life cycle [60]. Managing large ontologies may require the involvement of a team of experts to maintain and facilitate their reuse effectively. Additionally, large ontologies can lead to scalability issues and increase the complexity of reasoning [61]. In modularization, an ontology is divided into smaller, self-contained units called ontology modules. Each module has a distinct relationship with other modules and serves as a building block that can be reused and combined with other modules to create more intricate ontologies.

As mentioned in Section 2.1, this research established the 5 M model consisting of manpower, machine, material, method, and measurement to represent the fundamentals of the production process. However, the production process is a highly complex system involving logistics, technologies, organizations, and environments [62]. To cover the broad content of the production process activities, this paper's research was based on the modules of 5 M-based pilot ontologies. To reduce the complexity of InPro's development, a hybrid approach was adopted, combining four fundamental procedures: specification, knowledge acquisition and conceptualization, implementation, and evaluation. Additionally, the development of InPro leveraged an agile principle-based systematic framework for ontology building. This methodology provided a thorough conceptualization for each domain ontology module through multiple iterations, ensuring a robust and comprehensive representation of the production workflow. The procedure involved in developing the InPro is illustrated in Fig. 2, which will be presented in detail in the following subsections.

3.1. Ontology specification

The specification phase aims to clearly define the scope and objectives of the targeted ontologies, as well as to identify the intended users and ontology requirements [53]. In this section, the paper demonstrates the specification of the InPro ontology by addressing the following questions.

What is the purpose of ontology? This ontology is developed to represent concepts related to the industrial production workflow to support production process management and relevant industrial information integration from various systems and multiple sources.

What is the scope of the ontology? The ontology will allow the representation of the production workflow related to 5 M, manpower, machine, material, method, and measurement. The ontology covers concepts and relations regarding manpower, machine, material, method, and measurement, which are essential elements of the production process. The machine ontology module will be developed based on the OPC UA Companion Specifications related to robotics. This ontology will focus on describing the essential production process involving entities and their interrelations and attributes from a higher-level perspective.

Who are the end users of the ontology? (1) practitioners involved in the production activities; (2) system integrators for industrial information systems and software; (3) industrial software developers.

What is the intended use? The ontology is designed to function as a common knowledge management framework in the production domain. The software developers are the direct users to develop the software and applications integrating heterogeneous information leveraging ontology, from what the other users will benefit.

As presented in Fig. 3, the proposed ontological model enables the integration of various industry information systems, such as ERP, MES, warehouse management system (WMS), PLM, human resource management system (HRMS), and resources like OPC UA-based machine and IoT devices. This integration allows for the instantiation and storage of InPro classes and associated data in graph databases, accessible through an interface. The ontological model's capabilities facilitate several aspects of the production workflow. Production planning benefits from structured access to resources and their availability, helping optimize production schedules and resource allocation. Production managers can monitor processes more effectively through real-time data collection and analysis, enabling them to make informed decisions. Additionally, the ontological model allows for the collection of data on unqualified products, which can be used for failure analysis by quality engineers. This helps identify issues in the production process and implement corrective measures to improve product quality.

The purpose, domain, and scope of an ontology can be used to determine criteria for creating competency questions (CQs). By

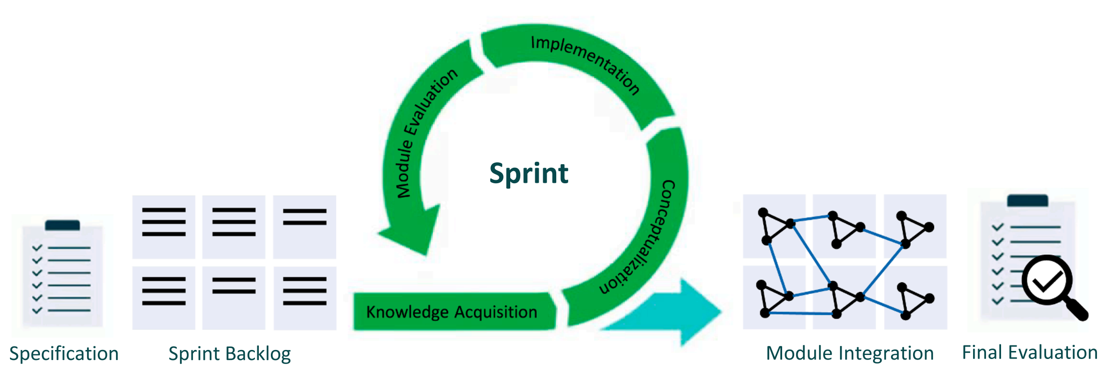


Fig. 2. Ontology development approach.

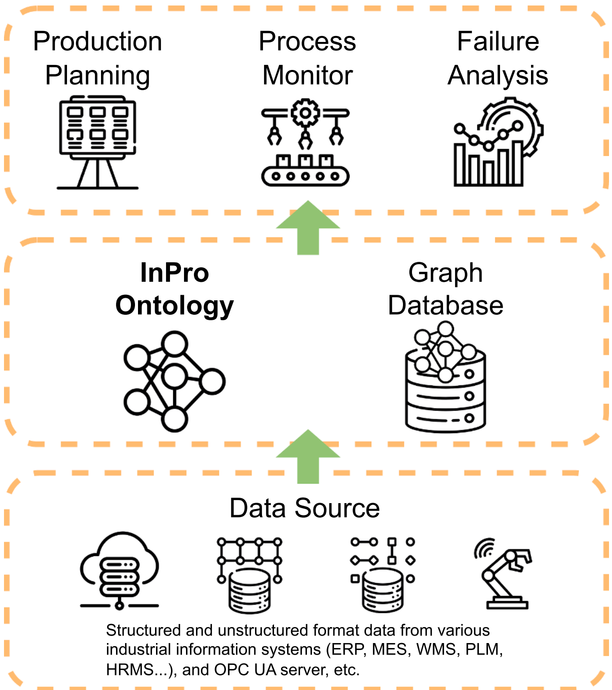


Fig. 3. Potential use of the InPro ontology.

formulating CQs, specific requirements for the ontology can be identified, and using CQs can aid in the ontology's development. The process involves expressing a list of requirements as questions to assess the ontology's capability to provide answers [63]. Table 1 presents a list of core competency questions that have been established to identify relevant concepts.

3.2. Sprint

Within Agile product development, a sprint is a time-constrained period in which specific tasks must be finished and ready for assessment. The InPro ontology was developed in seven sprints, with each sprint planning and backlog focusing on module ontology development separately (entities, agents, machines, materials, methods, measurements, and production processes). Each module of the ontology was developed based on the activities presented in Fig. 2, including knowledge acquisition and conceptualization, implementation, module evaluation, and module merging. Section 3.3 will introduce the evaluation in detail.

Table 1
List of core CQs.

No.	Competency questions (CQs)
CQ 1	What are the related entities to a production process?
CQ 1.1	Who is the agent of a production process?
CQ 1.1.1	What is the capability of an agent?
CQ 1.1.2	What is the availability status of an agent?
CQ 1.1.3	What are the tasks of an agent?
CQ 1.2	What is the machine of a production process?
CQ 1.2.1	Who is the controller of the machine?
CQ 1.2.2	What is the location of the machine?
CQ 1.3	What is the material of a production process?
CQ 1.3.1	What is the stock status of the material?
CQ 1.3.2	What is the supplier of the material?
CQ 1.3.3	What is the purchasing order of the material?
CQ 1.4	What is the process plan of a production process?
CQ 1.4.1	What is the status of the process plan?
CQ 1.4.2	What are the operations of a process plan?
CQ 1.5	What is the measurement process of the target measurand?
CQ 2	What is the target product and work shift of a production process?
CQ 3	What is the status of a production process?
CQ 4	What are the planned and final output quantity for a production process?

3.2.1. Knowledge acquisition and conceptualization

Knowledge acquisition based on literature review is the first step [64]. The knowledge acquisition captures all relevant terms in the domain knowledge during the literature phase. Based on our ontology development approach, each sprint aims at identifying relevant concepts for each ontology module and how diverse concepts can be connected in a knowledge domain, such as various classes, relationships, and properties.

The relevant knowledge for the development of the InPro ontology was obtained from multiple sources, including experts in the field, related literature, existing ontologies, and information models (as shown in Table 2). The specification and competency questions played a vital role in guiding the identification of relevant terms for the ontology. To gather input from domain experts, a weekly workshop was organized, providing an opportunity to collect valuable insights and feedback. The research activity was supported by the MACHINAIDE project [65], which is an international project, including academic and industrial partners. Knowledge acquisition does not strictly follow the Waterfall approach as an independent phase, it can be conducted simultaneously with other phases [66], which is also consistent with the notion of dynamic domain knowledge. Ontology can be extended or updated in response to the extraction of new knowledge at each stage of its lifecycle, resulting in changes and growth in its knowledge.

In the conceptualization phase that follows knowledge acquisition, the primary concepts obtained are used to develop a class hierarchy. This hierarchy includes defining class properties associated with these concepts and determining the domain and range of these properties [54]. To facilitate ontology development, the SKEM approach [54] recommends reusing and extending existing ontologies. Similarly, the NeOn approach [67] proposes leveraging and integrating existing ontological and non-ontological resources to avoid developing an ontology from scratch, thereby reducing development time and resources. Therefore, in the case of the machine module, it is developed based on the concepts, attributes, and properties of the OPC UA information model introduced in Section 2.3. The existing OPC UA information models are considered during the development of the machine ontology.

3.2.2. Implementation

The aim of ontology implementation is to convert the ontology model into a machine-readable model through an ontology representation language [51,71]. The W3C Web Ontology Language (OWL) is a Semantic Web language created to represent a domain knowledge about concepts, relations, and attributes [72]. As a computational logic-based language, OWL allows the computer to exploit the knowledge expressed in it, for instance, consistency checking, and reasoning. OWL document-based ontology can be publicly published and linked to or from other OWL ontologies [73]. To encode InPro into OWL, in this research, we use the Protégé editor. Protégé is a free, open-source ontology editor that was developed by Stanford University [74]. Its plug-in architecture

Table 2
Knowledge sources for the InPro ontology.

Major Concepts	Terms Examples	Sources
Machines	Controller, MotionDevice, SafetyState, TaskControl, AuxiliaryComponent, PowerTrain	OPC 40010-1 Robotics [68]
Materials	MRO, PurchasingOrder	[69,27]
Methods	ProcessPlan, Operation	ADACOR [22]
Measurements	MeasurementDatum, PlanSpecification, ObjectiveSpecification, MeasurandQuality	IAO [50], IOF [70]
Production Processes	ProductionOrder, Setup	ADACOR [22]

enables the construction of both elementary and complex ontology-based applications, which can be integrated with rule systems or other problem-solving programs to produce varied types of intelligent systems.

3.2.3. Module merging

Ontology merging is focused on developing a comprehensive InPro by specializing, extending, and adapting the developed ontology modules and existing ontologies. During the ontology development process, as different experts in various fields design the ontology modules separately during each sprint. This can lead to inconsistencies between modules, redundancy within modules, and incompleteness in the overall ontology. To address these issues and ensure a seamless integration of modules, expert workshops were conducted during each sprint. These workshops provided a platform for experts from different fields to collaborate and establish relationships between related concepts in different modules.

3.3. Evaluation

The evaluation of ontologies is generally defined as the process of assessing the quality of a given ontology based on a certain criterion to determine which of a collection of ontologies would be most suitable for a particular purpose [75]. In other words, ontology evaluation aims to ascertain its quality and correctness, which addresses several criteria: accuracy, adaptability, clarity, cohesion, completeness, computational efficiency, conciseness, consistency, coupling, and coverage [76]. Based on different targeted criteria, ontology evaluation techniques can be grouped into Gold standard-based, data-driven, task-based, and criteria-based approaches [61]. While the gold standard-based and data-driven approaches are appropriate for evaluating accuracy, completeness, conciseness, and coupling, the task-based approach is most effective for evaluating adaptability. The gold standard-based approach compares learned ontologies with benchmark ontologies, while the data-driven approach compares them with a reference text corpus [61].

In this study, due to the lack of a reference ontology and corpus, the criteria chosen to assess InPro were consistency, clarity, coverage, and adaptability. For consistency, the Pellet reasoner in Protégé was employed for automatic consistency checking, and expert workshops were used to evaluate clarity. To guarantee coverage, the answering of CQs was carried out. Adaptability was validated through a task-based approach based on two use cases, and SPARQL queries were written to retrieve relevant information for the production process. Moreover, given that each sprint focuses on accomplishing the development of one module, conducting a sole evaluation at the end could lead to increased inconsistency and inaccuracy. Hence, to address this concern, the evaluation process is divided into two parts: module evaluation, carried out during the sprint process to assess each module through automated consistency checking and expert workshops, and final evaluation, which involves automated consistency checking, expert workshops, and a task-based evaluation, specifically designed to evaluate the proposed InPro.

4. Industrial production workflow ontology (InPro)

This section illustrates the proposed InPro, including the core ontological model representing the knowledge of the production workflow, and the specifics of the InPro modules.

Fig. 4 illustrates the core ontological model of the InPro, which was built on the 5 M model described in Section 2.1. Mapping the ontology to a high-level abstraction framework guarantees that the terminologies utilized in the model are comprehensible to end-users and explicit to the ontology developers [77]. Thus, InPro utilized the BFO as an upper-level abstraction ontology. Moreover, one principle of IOF (introduced in Section 2.2) is the necessity to employ BFO as a top-level ontology [8], which further improves the interoperability of the InPro with IOF ontologies. Entities in the InPro, as the highest level of abstraction of all items related to the production workflow, can be classified as either *Occurrent* or *Continuant* according to the BFO. *Occurrent* class represents entities that occur, happen, unfold, or develop in time, while *Continuant* class defines elements with no relation to time, such as *Product*, *Material*, *Agent*, *Machine*, *Location*, and *Information Content Entity*. The *Process* class of *Occurrent* is applicable to *Planned Process*, as they take up a certain time interval for execution. The *Planned Process* involves two subclasses *Production Process* and *Measurement Process* to help describe the processes and activities in detail.

4.1. Entities module

The *Entities* module is depicted in Fig. 5, where the classes and properties (prefix: *isie*) are organized based on the BFO (prefix: *obo*). This module extended the core ontological model to provide a more comprehensive representation of entities in the temporal and spatial

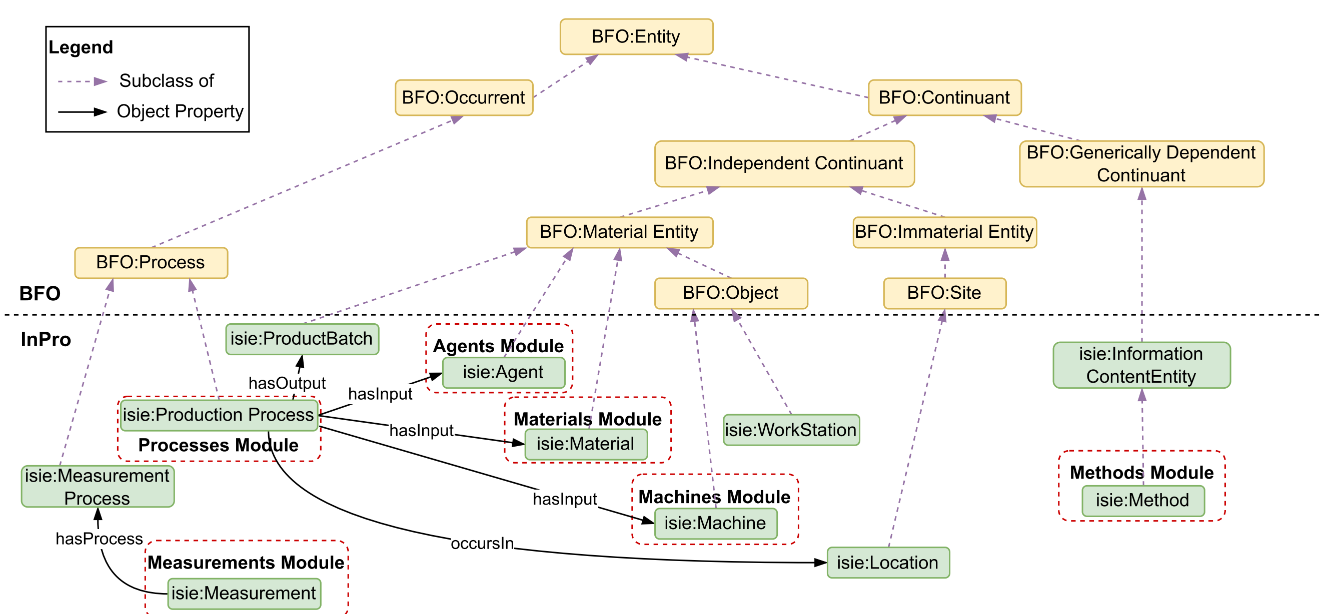


Fig. 4. The core ontological model.

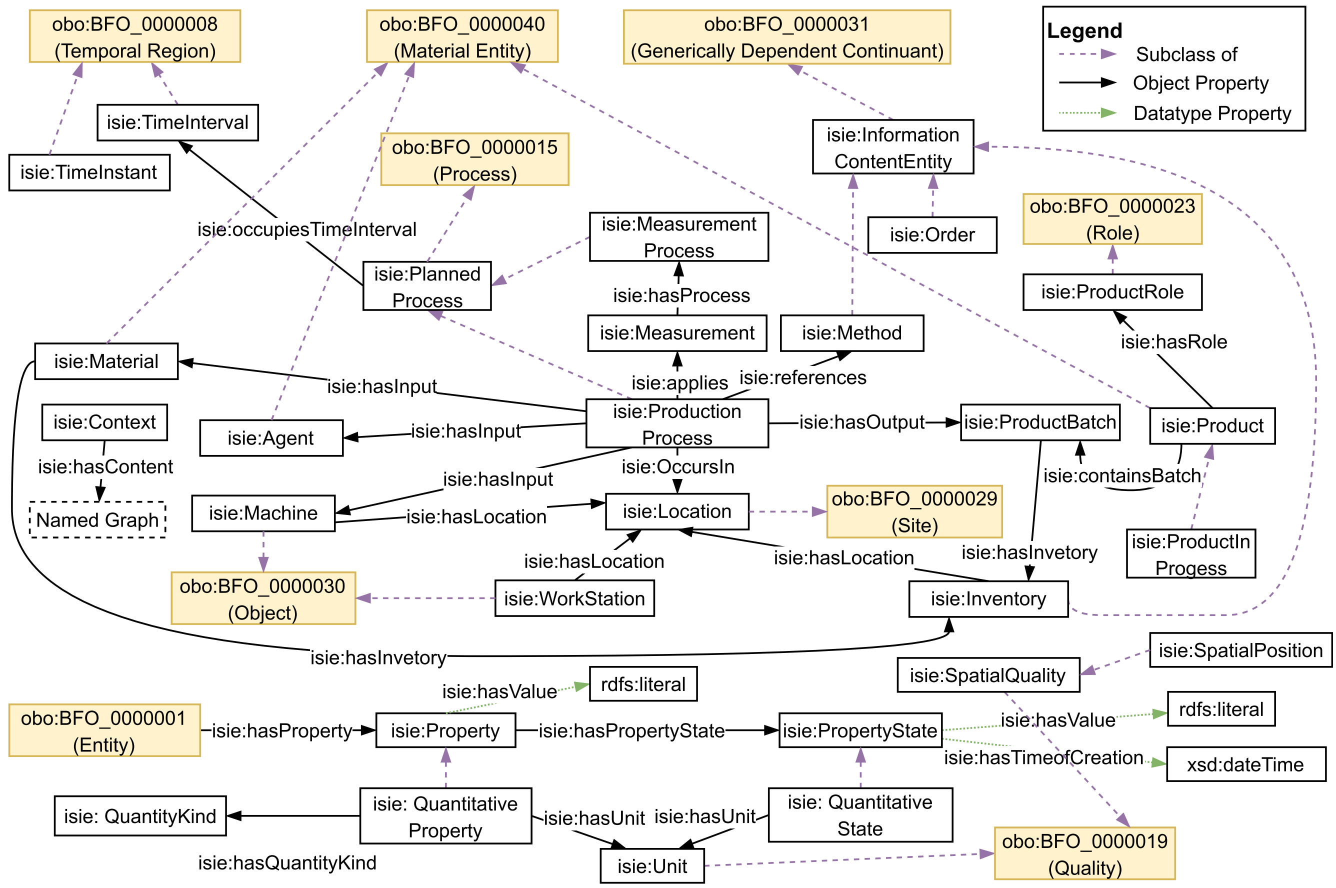


Fig. 5. Entities module of InPro.

domains, as well as allow the attachment of richer data about them with *Property* class. For example, in this module, the temporal and spatial entities were added to describe each module in their space and time attributes. The detailed definitions of core concepts for the *Entities* module are illustrated in Table 3.

Property and *PropertyState* are classes for objectifying properties in general, while *QuantitativeProperty* and *QuantitativeState* are subclasses for properties with numerical values. The *Property* class can be associated with a value directly through the datatype property *hasValue*, and the *PropertyState* allows the association of time (*isie:hasTimeOfCreation*). Meanwhile, the subclasses *QuantitativeProperty* and *QuantitativeState* can be related to the unit of measure (*isie:Unit*) and *QuantityKind* to represent static and dynamic numeric value. Additionally, manufacturing is a dynamic process and involves information from different contexts for the same entities. For example, a production process may be represented differently in the as-planned and actual production contexts with changed values of certain properties, or it may have various granularity of information based on different level-of-details. Therefore, InPro also takes the multi-context of the information into account. The InPro follows the contextual modeling approach from the DiCon that defines the *Context* class. The *Context* class refers to a realm of the data contents of related entities to which the data contents belong. Each Context has a *hasContent* property to an RDF named graph. This RDF named graph contains the RDF triples to represent the information based on the InPro. Such a contextual modeling approach avoids redundant modeling of the properties and property states to describe the multi-contextual information, as compared to the modeling approach of using different names of the properties to distinguish their contexts.

Table 3
General concepts for describing the entities.

Concepts	Definition
Inventory	*Inventory* is defined as goods in stock, such as product and material.
Location	*Location* is defined as a place where material entities can be located, or activities can occur.
Order	*Order* is defined as an authoritative documentation issued within a company.
ProductBatch	*ProductBatch* is defined as a quantity of a material related to the specific order.
ProductInProgress	*ProductInProgress* is defined as unfinished goods awaiting completion.
SpatialPosition	*SpatialPosition* is defined as a position in a space.
SpatialQuality	*SpatialQuality* is defined as a quality that states the spatial states of an entity.
WorkStation	*WorkStation* is defined as a workspace in the factory.

4.2. Agents module

Fig. 6 represents the *Agents* module that is annotated with the prefix: *isia*. The *Agent*, corresponding to manpower in the 5 M model, has a subclass *Personnel*. The classes and properties, such as *Division*, *Position*, and *reportsTo* enable the knowledge representation of organizational relations for an employee. The *Training* and *Capability* classes were included to determine the personnel's capabilities, which can be matched against the specific requirements of the production operational task, such as the overhead crane operation requiring a crane driver license. The *JobSchedule* class refers to the specified days and times (defined by *Workshift*) that an employee is expected to complete the tasks (represented by *ShiftTask*) of their employment position in the specific location (described by *Location*). Small and medium sized enterprises (SMEs) are able to develop their own HRMS following the structure of the *Agents* module.

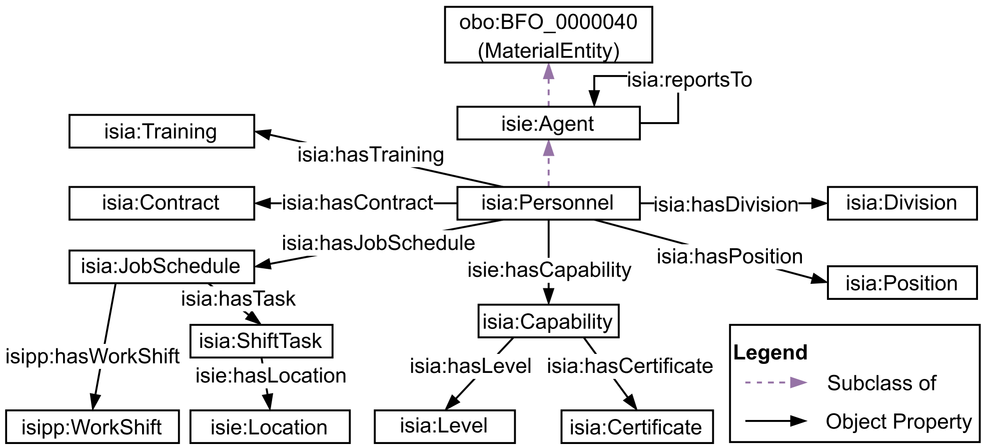


Fig. 6. Agents module of InPro.

4.3. Machines module

As indicated in Sections 2.3 and 3.1, the *Machines* module (prefix: *isimach*) presents the knowledge representation of robotics using OPC 40010-1 Robotics, as illustrated in Fig. 7. Table 4 provides detailed definitions of important concepts. Overall, the *Machine* model consists of *MotionDevice*, *Controller*, and *SafetyState*. The *Motor* is driven by the *Dirve* from *Controller*, which is situated within the *PowerTrain*. Additionally, the *Property* defined in the *Entities* module was employed to represent the dynamic data of each class.

4.4. Materials module

To describe the material involved in the production process, Fig. 8 illustrates the *Materials* module (prefix:*isimatl*). The *Material* class is composed of two subclasses: *RawMaterial* and *MRO*. Raw materials are initial products employed in a manufacturing process to produce a new one, which can be further classified into direct and indirect materials. Direct materials are components of the finished product, whereas indirect materials are consumed during production without being included in the final product. MRO (maintenance, repair, and operations) [69] is essential to support the overall operations, including items such as tools, consumables, asset maintenance supplies, and spare parts, that are not necessary components of the finished product. The *Inventory* class of the *Materials* module is composed of *InplantInventory* and *Warehouse-Inventory* to record all materials currently in stock that have not yet been used in work-in-progress. In addition, the *Order* class involves two subclasses: Production orders produced by the company and Purchasing orders made by external entities. Production orders refer to products in progress, while purchase orders are necessary for the procurement of items, requiring data relating to the supplier, cost unit, and delivery, as well as the item, delivery date, and any specified requirements. We also defined *MaterialBatch* to represent a homogeneous unit with unique specifications for quality traceability.

Table 4
General concepts for describing the robotics.

Concepts	Definition
MotionDevice	*MotionDevice* is defined as an independent motion device, such as a manipulator or linear axis.
Axis	*Axis* is defined as an axis of a motion device.
PowerTrain	*PowerTrain* is defined as a power train of a motion device. One power train can consist of various motors and gears.
Motor	*Motor* is defined as a motor of power train.
Gear	*Gear* is defined as a gear of a power train, which is connected to the corresponding motor.
AuxiliaryComponent	*AuxiliaryComponent* is defined as a component mounted in a control cabinet or a motion device.
SafetyState	*SafetyState* is defined as the safety states of the motion devices and controllers.
Controller	*Controller* is defined as the control unit of motion devices.
Drive	*Drive* is defined as a drive mounted in a controller.
TaskControl	*TaskControl* is defined to describe an execution engine that loads and runs task programs.

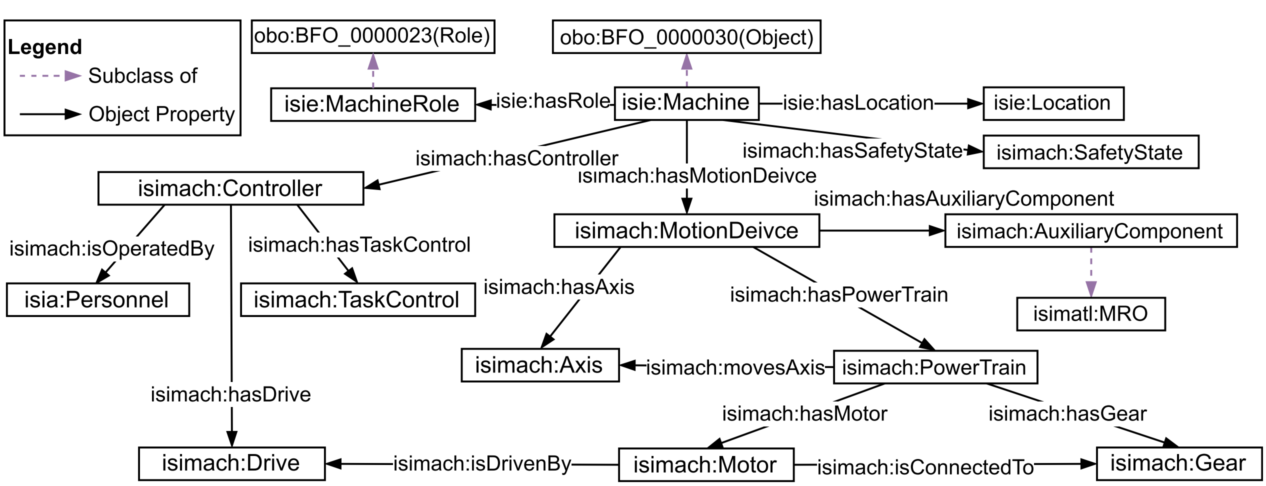


Fig. 7. Machines module of InPro.

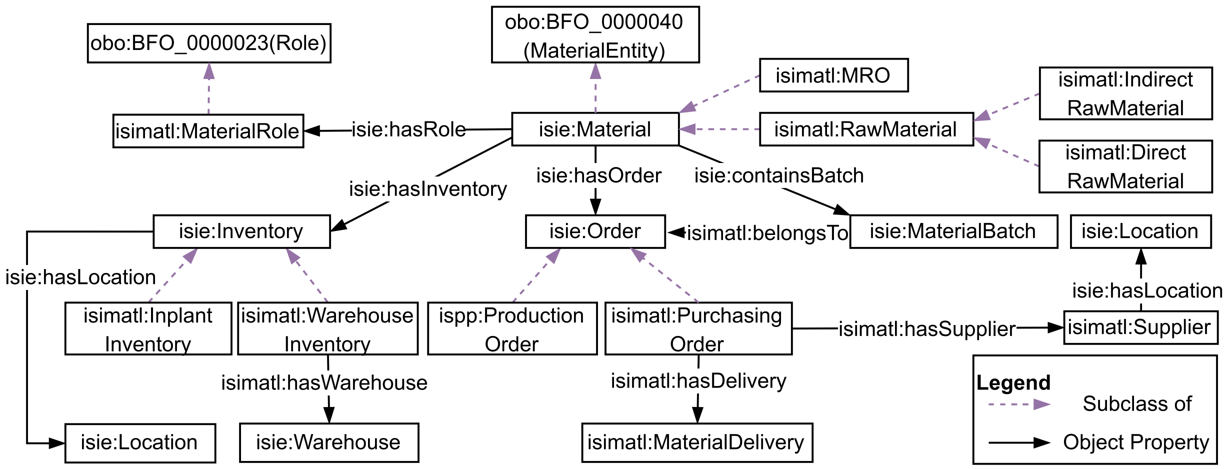


Fig. 8. Materials module of InPro.

4.5. Methods module

The *Methods* module (prefix: *isimeth*) depicted in Fig. 9 is essential for the production process, enabling efficient production. Having a clear process plan and operations in place optimizes production, making it more cost-effective and reliable. It also ensures that the product meets customer requirements and is produced optimally. The *ProcessPlan* class outlines the steps necessary for the production of a product, while the *Operation* class specifies the particular activities and tasks associated with each step. The *Capability* class identifies the necessary qualification of the employee, while the *AgentQty* class defines the quantity of the agent for the operation. The *MaterialList* class outlines all the materials needed for an operational task, which can also be considered a breakdown of the mBOM (manufacturing bills of material) at the operational level. Lastly, the *Instruction* class supplies an in-depth description of each operation.

4.6. Measurements module

The *Measurements* module (prefix: *isimeas*) shown in Fig. 10 is designed to provide the basic representational capabilities for various measurements involved in the production process. It mainly contains the quality measurement of the machine, product, and material. The core of this module is the *MeasurementProcess* class, which is a subclass of the *PlannedProcess*. The specified output of this class is the measurement datum, which represents a quality measurement of the measurand. This datum can be recorded as a category label (e.g. limit gauges labeled as"Go" or"No-Go") or as a numerical value (e.g. length, weight, and temperature). A measurement process is a concretization of a measurement plan, which includes an action specification and a conditional specification. The *ActionSpecification* is a directive information entity that describes the action to be taken (e.g. operator should use a caliper to measure the length of the part ten times), while the *ConditionalSpecification* is a directive information entity that outlines what should take place when certain conditions are met (e.g. the length of the part should be measured at specific temperature and humidity). Moreover, the *ObjectiveSpecification* is a directive information object that describes the process endpoint to be achieved by the measurement process.

4.7. Production processes module

The *ProductionProcesses* module (prefix: *isipp*) serves as the cornerstone of InPro, integrating the 5 M-based modular ontologies, as depicted in Fig. 11. A production order is used to specify the material to be produced, the plant where the production is to take place, the date and time of production, and the required quantity of goods. Such a production order is typically generated by a sales order. The seller creates a sales order with the customer's requested details for the goods or services. Additionally, the Bill of Materials (BOM) is transferred to the production order, resulting in the list of components for the order. Fig. 12 shows the workflow of the production process, representing the relation between the *Production Processes* module and the *Methods* module. An operational task, similar to *WorkOrder* in ADACOR ontology [22], is defined as a request for a unit of work to be accomplished. It is the lowest level scheduled objects involved by material batch, machine, and agent. The *Setup* defines the preliminary preparation for the corresponding operational tasks. The *ProductionPlanning* class delineates the activities necessary to meet a production requirement based on the *ProcessPlan*. Production planning consists of one or more production processes, and each production process is made up of one or more operational tasks that detail the work to be executed at a workstation.

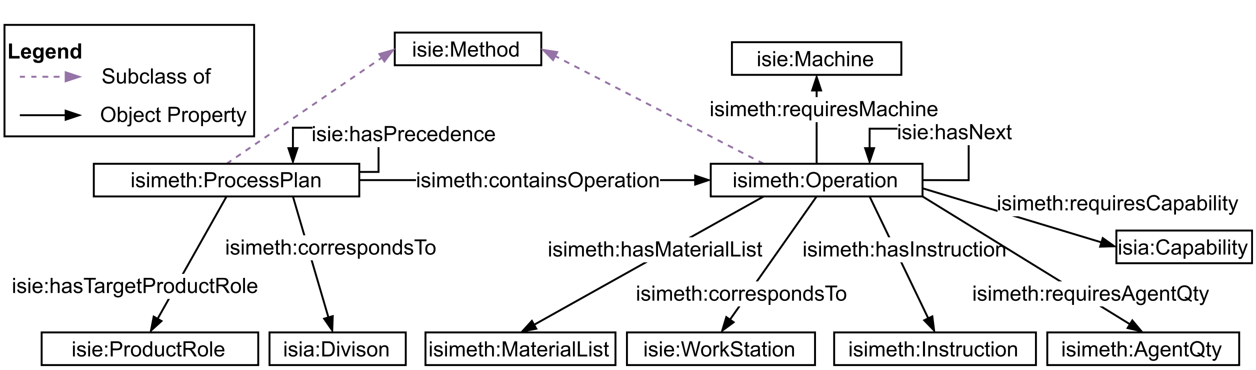


Fig. 9. Methods module of InPro.

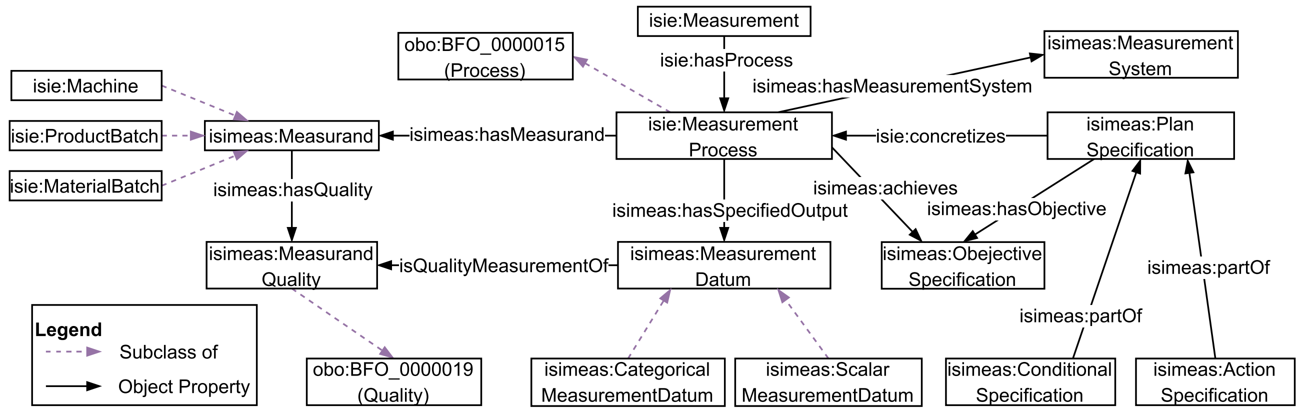


Fig. 10. Measurements module of InPro.

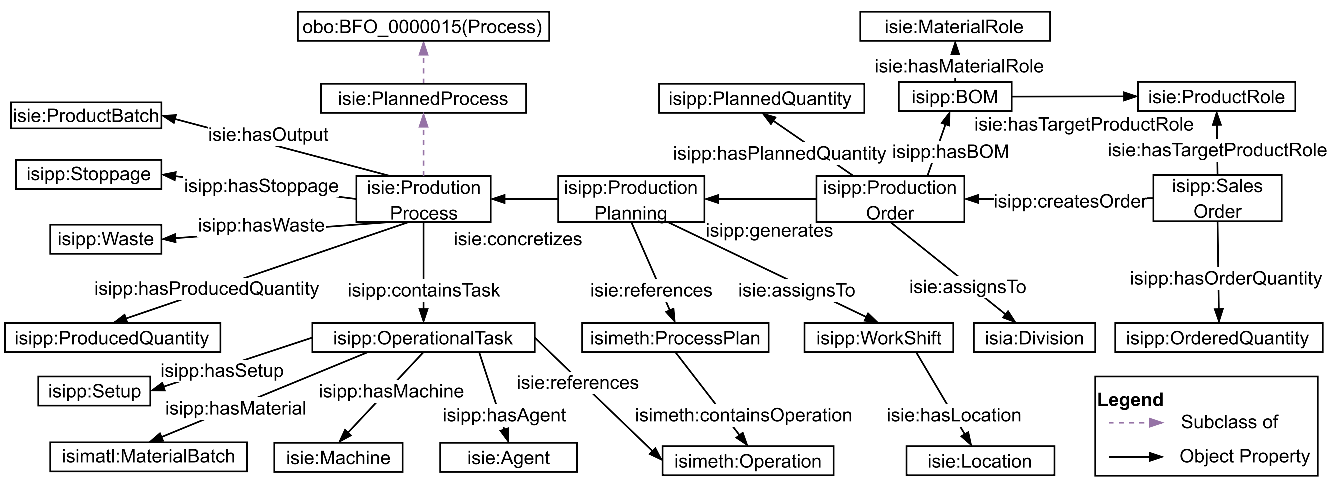


Fig. 11. Production Processes module of InPro.

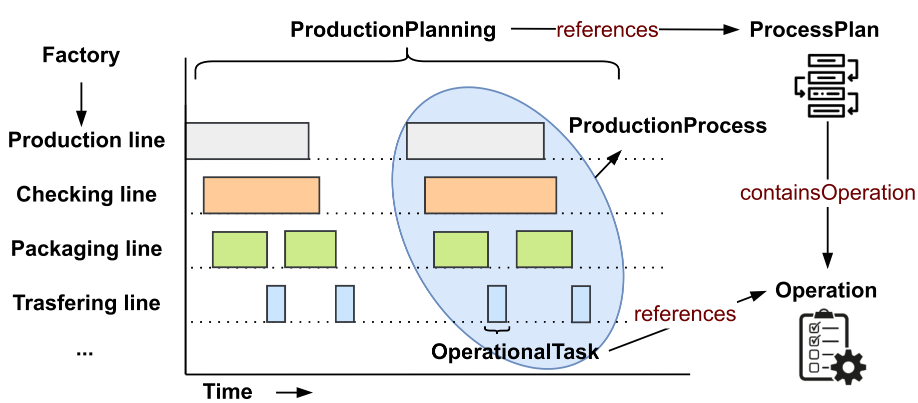


Fig. 12. The workflow of the production process.

Each operation task has an associated procedure, which is defined as the *Operation* in the *Methods* module. The *ProductionProcess* has the final product batch or immediate product batch as the output, and it also records stoppage for OEE (Overall Equipment Effectiveness) analysis, and waste during production.

4.8. Existing ontologies alignment

The InPro was constructed with the intention of reusing and integrating existing ontologies and semantic resources without redundant ontology modeling. Consequently, apart from using the BFO as the top-level base and the OPC UA Companion Specification as the *Machines* module, relevant existing ontologies were assessed and then matched with the InPro. Fig. 13 shows the alignment of those ontologies to the corresponding classes in the InPro ontology, including IOF [78,70], FOAF [79], OWL-TIME, SAREF [80], SOSA [81], QUDT [82], and BOT ontologies. The IOF core ontology was used to represent the high-level knowledge (*isie:PlannedProcess* and *isie:InformationContentEntity*), which is unambiguous for further ontology integration and extension. The FOAF Ontology was used as a reference to describe and formalize

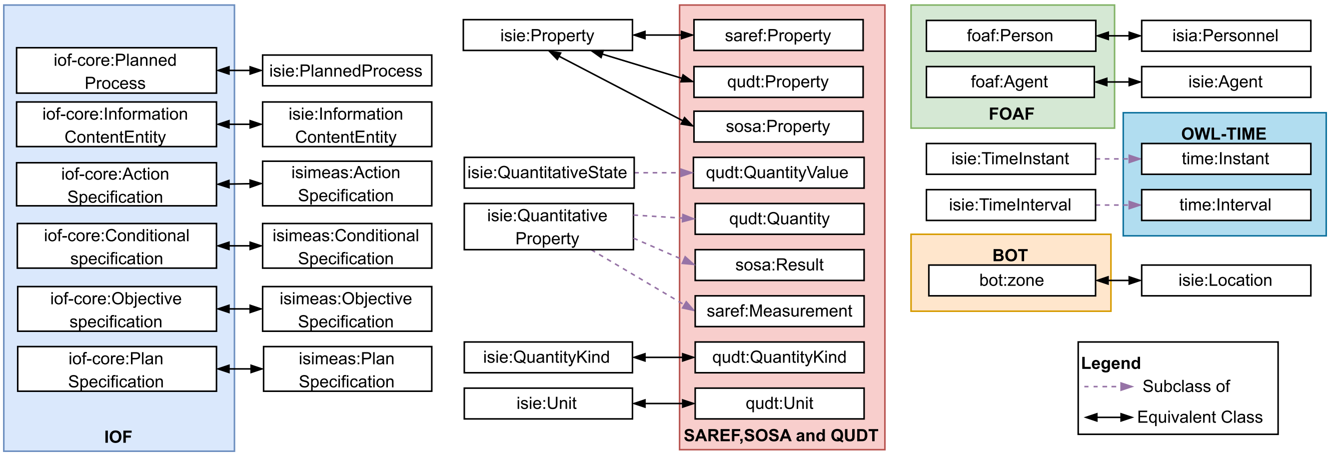


Fig. 13. The alignment of the InPro with existing ontologies.

the agents involved in production. The SOSA, QUDT, and SAREF Ontologies were utilized to characterize sensor observations, which are essential data streams in production workflow monitoring. The BOT Ontology's spatial element classes (bot: Zone) were linked to the *Location* in the InPro, providing a gateway to connect BIM data and use their product or spatial information, as well as related information. For example, the *Property* class of the InPro is equivalent to *saref:Property*, *qudt:Property*, and *sosa:Property*. Additionally, *QuantitativeState* is a subclass of *qudt:QuantityValue*, while *QuantitativeProperty* is a subclass of *qudt:Qiantity*, *sosa:Result*, and *saref:Measurement*. Moreover, *QuantityKind* and *unit* classes are analogous to *qudt:QuantityKind* and *qudt:Unit*, respectively.

5. Ontology evaluation

This paper outlines the evaluation process of the InPro, including the ontology evaluation approaches used, and presents the results obtained. Automated consistency checking and expert workshops are used to evaluate the InPro during each sprint and the final evaluation. Additionally, a task-based evaluation is only conducted for the final evaluation to validate the feasibility of the InPro.

5.1. Automated consistency checking

This research used Pellet, an open-source OWL-DL reasoner, to perform consistency checking of an ontology-based on description logic (DL) principles. According to [83], Pellet provides"reasoning support for individuals, user-defined datatypes, and debugging support for ontologies". The debug function in Protégé, using the Pellet reasoner, confirmed that the InPro ontology was consistent and coherent.

5.2. Expert workshops

Involving domain experts in the evaluation process ensures the accuracy and completeness of an ontology [84]. The evaluation of the InPro ontology by domain experts was conducted to ensure the terms and relationships were adequately represented. During the evaluation, workshop experts reviewed the concepts in the InPro ontology, discussed alternative knowledge structures, and identified any missing information. As a result of their feedback, the ontological model has adjusted accordingly, shown in Table 5. Experts suggested defining a concept to represent the variable in the InPro. The initial ontology represented the variable through the attributes individually. Therefore, the class *Property* was defined to indicate the variable for all the related entities. Experts indicated that the mobile machine requires a concept to represent the spatial position, which allows the machine to accurately identify its coordination and adjust its behavior accordingly. In some cases, such as autonomous vehicles, it is essential that the machine knows its exact position to safely navigate its environment. Moreover, experts indicated the *ProductionProcess* needs to be represented as multi-context information. This is due to two reasons. First, based on the different information granularity in the various information systems, the representation of the same production process-related entity would be different. Second, because of the dynamic nature of the production process, the same entity's state value would be updated temporally. Thus, it requires multi-context information to represent the entity's information under different contexts.

Table 5
Ontology adjustments according to experts' feedback.

Recommendation or issue	Modification
To include a concept to represent the intermediate good during the production process.	The class *ProductInProgess* was defined as part of the class *Product* to represent a semi-finished product used to produce a final good or finished product.
To include a concept to represent the spatial position of the mobile machine.	The class *SpatialPosition* was defined to indicate cartesian position expressed as x, y, and z coordinates with respect to a spatial origin and spatial orientation.
To include a concept to represent the tasks for class *JobSchedule*.	The class *ShiftTask* was defined to represent the working activities for the daily job schedule.
To include a concept to represent the variable in the InPro.	*Property* was created to indicate the value in a general way, and *QuantitativeProperty* was defined as part of the class *Property* to represent quantitative value.
The material used during the production is partly from purchase, and partly from self production.	The relation between material planning and production order was created.
To include a concept to represent multi-context information of the class *ProductionProcess*.	The *Context* was created as part of the class *InformationContextEntity* to describe various contexts and further indicate the different states of the production process.

5.3. Answering CQs

A set of CQs listed in Table 1 was initially employed by both participants and experts to logically recognize the pertinent concepts and relationships. Then, a task-based evaluation was conducted using a specific set of CQs (see Table 7 and Table 9), where practical information was used to answer the questions. The results show that InPro is able to retrieve accurate information to answer the CQs.

5.4. Task-based evaluation

The utility of InPro was evaluated by employing task evaluation to assess the advantages of practical data as instance information. To illustrate the practical application of ontology, two cases were selected: information retrieval for production planning and failure analysis.

The transformation pipeline employed to link data from the heterogeneous systems to the InPro and to create graph-based data sets is displayed in Fig. 14. Data sources, from various industrial information systems, were first analyzed and manually matched to the InPro ontology, with HRMS provided the agent's schedule and task for the production activities, WMS provided material inventory and delivery information, PLM furnished the process plan and operation details, MES supplied production process information from raw material to the final product, and ERP provided business activities, including production orders and sales orders. All the data was acquired in tabular format and OpenRefine, an open-source application, was used to transform it into Resource Description Framework (RDF) format to instantiate the InPro. Subsequently, RDF graphs were aligned and stored in the Graph database with the ontology. Finally, SPARQL queries were implemented to retrieve instance data and answer task-based CQs.

5.4.1. Case 1. Production planning

The production process involves the interaction of multiple practitioners with multiple industrial systems: HRMS, PLM, WMS, MES, and ERP. The static and/or dynamic data and availability of resources in these systems are essential for the manufacturing enterprise to make operational decisions. Each of the applications has its own data models, apart from those modules provided by single software vendors, which are isolated in silos. To enable true interoperability, it is necessary to capture the semantic meaning of the data so that different applications can recognize it. This case included a set of SPARQL queries aimed to extract essential information about the production planning, which are also performed as answering the task-based CQs.

Table 6 showed three queries that corresponded to the task-based CQs (presented in Table 7). CQ.1 to CQ.4 were answered by the first query, which allowed for the retrieval of the target product, its planned output quantity, and details about the corresponding work shift of the production order"PO1002″. Subsequently, the second query was employed to determine the number of available agents for the target work shift, with the purpose of organizing the production process. Finally, the third query, relating to CQs 6–9, supplied information on material stock status, the required machine, and the process plan. The results of the information retrieval for this case were displayed in Fig. 15. The InPro thus facilitates the retrieval of information related to production targets, necessary resources, the entire schedule, and all the steps that form part of the production process and their correlations.

Table 6
SPARQL statements for the production planning case.

```
PREFIX isie: <https://w3id.org/IndustrialSystemIntegration/Entities#>
  PREFIX isia: <https://w3id.org/IndustrialSystemIntegration/Agents#>
  PREFIX isimatl: <https://w3id.org/IndustrialSystemIntegration/Material#>
  PREFIX isimeth: <https://w3id.org/IndustrialSystemIntegration/Methods#>
  PREFIX isimeas: <https://w3id.org/IndustrialSystemIntegration/Measurement#>
  PREFIX isipp: <https://w3id.
  org/IndustrialSystemIntegration/ProductionProcess#> PREFIX ex: <https://exa
  mple.org/
  #CQ 1–4
  SELECT?ProductRole?WorkShift?Date?Start?End?PlannedQuantityValue
  WHERE{
  ?SalesOrder isipp:createsOrder ex:PO1002; isie:hasTargetProductRole?
  ProductRole.
  ex:PO1002 isipp:generates?ProductionPlanning.
  ?ProductionPlanning isie:assignsTo?WorkShift.
  ?WorkShift isia:hasAvailableDate?Date; isipp:hasStartTime?Start; isipp:
  hasEndTime?End.
  ex:PO1002 isie:hasProperty?PlannedQuantityProperty.
  ?PlannedQuantityProperty isie:hasQuantityKind isipp:PlannedQuantity.
  ?PlannedQuantityProperty isie:hasPropertyState?PlannedQuantityState.
  ?PlannedQuantityState isie:hasValue?PlannedQuantityValue.}
#CQ 5
  SELECT (COUNT(?JobSchedule) as?Total)
  WHERE{
  ?JobSchedule isipp:hasWorkShift ex:WorkShift1; isie:hasProperty?
  JobScheduleProperty.
  ?JobScheduleProperty isie:hasPropertyState?JobScheduleState.
  ?JobScheduleState isie:hasValue?StateValue. FILTER(?StateValue="Available") }
#CQ 6-9
  SELECT?MaterialQty?StockStatus?ProcessPlan?Machine
  WHERE{
  ex:PO1002 isipp:hasBOM?BOM.
  ?BOM isipp:hasMaterialRole?MaterialRole.
  ex:ZG011AQA isie:hasRole?MaterialRole.
  ?MaterialRole isie:hasProperty?MaterialQtyProperty.
  ?MaterialQtyProperty isie:hasQuantityKind isimatl:MateiralQuantityPerUnit.
  ?MaterialQtyProperty isie:hasValue?MaterialQty.
  ex:ZG011AQA isie:hasInventory?Inventory.
  ?Inventory isie:hasProperty?InventoryProperty.
  ?InventoryProperty isie:hasPropertyState?InventoryState.
  ?InventoryState isie:hasValue?StockStatus.
  ex:PO1002 isipp:generates?ProdcutionPlanning.
  ?ProdcutionPlanning isie:references?ProcessPlan.
  ex:VW321-01-001-01_1.1 isimeth:requiresMachine?Machine.}
```

5.4.2. Case 2 production failure analysis

Root Cause Analysis (RCA) is a methodical approach to identifying and assessing the relationships between various events and issues that may have contributed to an incident [85]. The goal of RCA is to identify

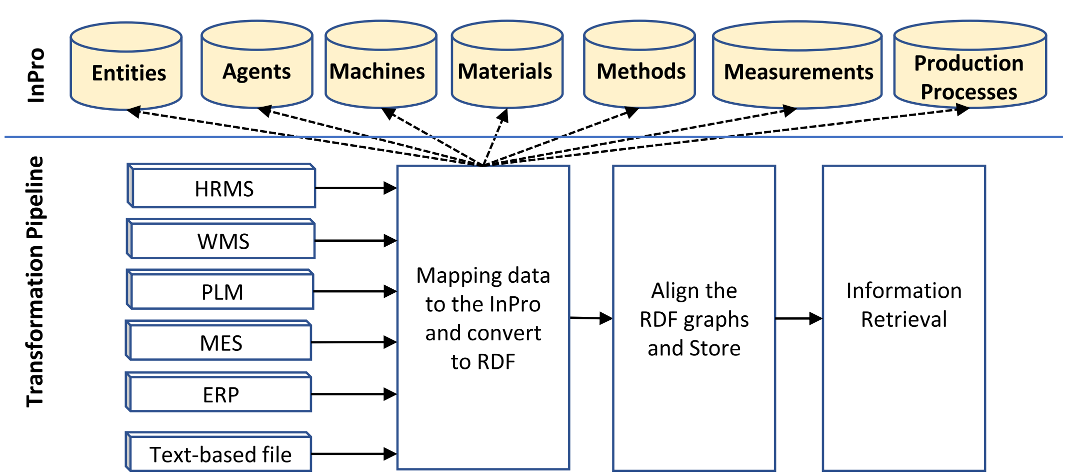


Fig. 14. The transformation pipeline for the use cases.

Table 7
Specified CQs and answers based on the production planning case.

Specified Competency questions	Answers
1. What is the target product of the production order PO1002?	Product A
2. What is the work shift of the production order PO1002?	WorkShift1
3. What is the date and time of the work shift WorkShift1?	17/04/2023, 8:00, 16:00
4. What are the planned output quantities for the production order PO1002?	10
5. How many agents will be available for the work shift Work Shift1?	24
6. What is the quantity of material ZG011AQA required to produce a product A?	2
7. What is the stock status of the material ZG011AQA?	LimitedStock
8. What is the process plan for the production order PO1002?	AIIC0082
9. What machine is required for operation VW321-01-001-01_1.1?	AIIC03201

the source of the problem and then take the necessary steps to eliminate it and prevent it from happening again. The 5 M (manpower, machine, material, method, and measurement) can be five categories that are used to determine the origin of the problem in the RCA process [86].

To demonstrate the use of InPro in locating resources for a quality issue related production process, the second case was conducted. Table 8 displays two queries to answer the task-based CQs (presented in Table 9). The first query was related to CQ.1 and CQ.2 and was used to obtain the status of the production order"PO1001″, the planned and actual output quantity. Fig. 16 illustrates the status of the production order as a quality issue and initializes the potential operational task related to this quality problem. The second query related to CQs 3–7 produces the agent, material batch, product batch, and measurement process related to this potential operational task, providing source information for further failure analysis based on RCA. This use case highlights that the 5 M-based InPro is useful for failure analysis.

6. Discussion, limitations, and future works

The heterogeneity of information is the main obstacle to integrating multiple information systems and various IoT data in industries. Despite the fact that ontology enables the unambiguous representation and definition of knowledge in diverse information systems, the information model of the production workflow is still lacking. To tackle this issue, we created the InPro ontology. The main contributions of the proposed InPro are (1) providing a domain knowledge representation of the production workflow related to robotics; (2) providing a formalized vocabulary for describing the production workflow information among the heterogeneous systems and facilitating the interoperability problem; (3) improving the utilization of the production workflow information leveraging linked data and Semantic Web technologies.

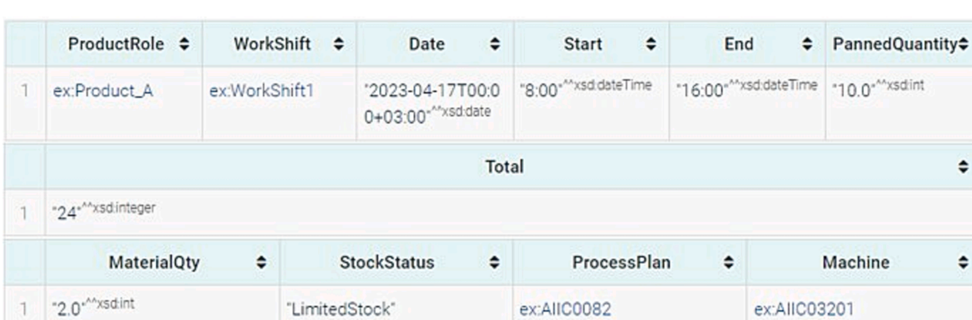
First, this paper presented InPro which was built to systematically represent production workflow knowledge and information. The InPro was created through the acquisition of domain knowledge about the production workflow, leveraging the 5 M model and OPC UA Companion Specification. The current production process involves a complicated and dynamic information system. While existing models like the 5 M-based model to present a structure for recognizing and managing the essential facets of a production process, they are built as theoretical models that cannot be directly used as an information model. In this study, the 5 M model was implemented in the InPro ontology development, demonstrating how it can be applied to acquire domain knowledge. The results of this study indicate that the 5 M model can be highly beneficial for designing models for diverse applications in the manufacturing domain. Additionally, OPC UA, with its standardized

Table 8
SPARQL statements for the failure analysis case.

```
#CQ 1–2
  SELECT?Status?PlannedQuantityValue?ProducedQuantityValue
  WHERE{
  ex:PO1001 isie:hasProperty?PO1001Property.
  ?PO1001Property isie:hasPropertyState?PO1001State.
  ?PO1001State isie:hasValue?Status.
  ex:PO1001 isie:hasProperty?PlannedQuantityProperty.
  ?PlannedQuantityProperty isie:hasQuantityKind isipp:PlannedQuantity.
  ?PlannedQuantityProperty isie:hasPropertyState?PlannedQuantityState.
  ?PlannedQuantityState isie:hasValue?PlannedQuantityValue.
  ?ProductionProcess isie:hasProperty?ProceducedQuantityProperty.
  ?ProceducedQuantityProperty isie:hasQuantityKind isipp:ProducedQuantity.
  ?ProceducedQuantityProperty isie:hasPropertyState?ProceducedQuantityState.
  ?ProceducedQuantityState isie:hasValue?ProducedQuantityValue.}
#CQ 3–7
  SELECT?OperationalTask?Agent?MaterialBatch?ProductBatch?
  MeasurementProcess
  WHERE{
  ?Operation isimeth:correspondsTo ex:WorkStation13.
  ?OperationalTask isie:references?Operation.
  ?OperationalTask isipp:hasAgent?Agent.
  ?OperationalTask isipp:hasMaterial?MaterialBatch.
  ex:PO1001 isipp:generates?ProductionPlanning.
  ?ProductionPlanning isie:concretizes?ProductionProcess.
  ?ProductionProcess isie:hasOutput?ProductBatch.
  ?MeasurementProcess isimeas:hasMeasurand?ProductBatch.}
```

Table 9
Specified CQs and answers based on the failure analysis case.

Specified Competency questions	Answers
1. What is the status of the production order PO1001?	lack of production
2. What is the planned and final output of the production order PO1001?	100, 95
3. What is the operational task in WorkStation13 of the production order PO1001?	PP100111_VW321-01–001-13
4. Who is the operator of this operational task?	AIIC001
5. What material batch is used for this operational task?	ZG011AQA_Batch_1
6. What is the product batch of the production order?	ProductBatch_PP100111
7. What is the measurement process of the production batch ProductBatch_PP100111?	MeasurementProcess1



	ProductRole	WorkShift	Date	Start	End	PannedQuantity
1	ex:Product_A	ex:WorkShift1	"2023-04-17T00:00+03:00"^^xsd:date	"8:00"^^xsd:dateTime	"16:00"^^xsd:dateTime	"10.0"^^xsd:int

	Total
1	"24"^^xsd:integer

	MaterialQty	StockStatus	ProcessPlan	Machine
1	"2.0"^^xsd:int	"LimitedStock"	ex:AIIC0082	ex:AIIC03201

Fig. 15. Querying information for CQs of Case 1.

	Status	PlannedQuantity	ProducedQuantity
1	"lack of production (Quality issue)"	"100.0"^^xsd:int	"95.0"^^xsd:int

	OperationalTask	Agent	MaterialBatch	ProductBatch	MeasurementProcess
1	ex:PP100111_VW321-01-001-13	ex:AIIC001	ex:ZG011AQA_Batch_1	ex:ProductBatch_PP100111	ex:MesurementProcess1

Fig. 16. Querying information for CQs of Case 2.

semantic information model, offers an optimal solution for acquiring domain knowledge of machine. This study developed the production workflow concerning robotics based on the OPC 40010-1 Robotics, which enables the direct integration of the OPC UA server and other industrial systems in an interoperable way.

Second, various industrial systems are widely utilized in the manufacturing industry to facilitate decision-making and action-taking. These systems are often implemented with custom software created for specific projects. As a result of this fragmented origin, industrial systems are typically established as individual entities, rather than components of a larger system involving multiple stakeholders. The purpose of the proposed ontology is to address this issue by providing a formalized vocabulary that can integrate knowledge and information from different contexts and various systems. The large amount of heterogeneous data involved in the production workflow can be enhanced with the use of InPro to enable efficient data sharing between organizations, improving communication and collaboration, and ensuring data quality and accuracy. This allows data from various sources to be combined, providing an efficient and reliable overview of the systems, processes, and components. The evaluation results demonstrated the ability of InPro to integrate information from multiple sources.

Finally, InPro has been shown to be an effective platform for production workflow information management using linked data and Semantic Web applications. Through task-driven evaluation, its feasibility in solving the semantic interoperability problem of production workflow information has been demonstrated. Moreover, two use cases have illustrated its ability to retrieve information from various systems using SPARQL. InPro can also be used for essential management functions, such as tracking material flow, rescheduling production, identifying production constraints, and optimizing production efficiency. These features make InPro an excellent choice for production workflow information management.

This research has identified the following limitations of the developed ontology. First, InPro is a higher-level ontology that captures fundamental concepts and properties for representing production workflow digitally. However, InPro does not provide detailed classification hierarchies for domain entities, which may need to be added for specific use cases to effectively represent the production workflow. For instance, the *Materials* module represents knowledge about the material flow and stock within the production process domain rather than chemical, thermal, and mechanical properties.

The 5 M model was employed to characterize the core components of the production workflow; however, it should be noted that cost, safety, and maintenance are also integral aspects of the production process. Relevant ontologies have been proposed in these domains. For instance, Tham et al. [87] presented a core cost ontology and micro-theory of costing for enterprise modeling that includes representations of activities, activity statuses, time, causality, and resources. Additionally, safety ontology has been extensively studied in the construction domain based on BIM [88]. IOF provided a minimal reference ontology for maintenance concepts commonly used in maintenance application ontologies. Due to the extendibility and connectivity of ontology, we can reuse the existing ontological resources to extend the concept of InPro.

In this study, the machine module was created based on the OPC 40010-1 Robotics, which can also be developed based on other existing OPC UA Companion Specification. For instance, a Computer Numerical Control (CNC) machine module can be effectively designed by utilizing the OPC 40502-1 CNC Systems standard [89], while an Additive Manufacturing module can be developed using the OPC 40540 UA standard [90]. However, the OPC UA Companion Specification is still a work in progress, limiting its ability to represent all types of machines. This has consequently limited the utilization of the machine module in InPro. To address this, end users may need to develop the machine module leveraging high-level OPC UA information models like OPC UA DI (Device Integration) [91]. Additionally, the continuous updates of high-frequency OPC UA data impose a heavy workload on the SPARQL query engine triple store. Hence, we did not implement the practical data transmission from the OPC UA server to the machine instance of InPro in this work. We are currently exploring the possibility of obtaining this high-frequency dynamic data directly from the OPC UA server, instead of acquiring data from the graph database.

Moreover, ontology evaluation is a complex process that necessitates the consideration of several decision criteria to identify the elements of quality to be evaluated [76]. It has been the responsibility of the evaluator to decide which criteria should be evaluated and the optimal threshold for each criterion [92]. However, this introduces the issue of subjectivity in the scientific undertaking. To address this, a data-driven approach can be adopted to quantify the impact of bias on the results of the evaluation [76]. The vector space representation of terms from the corpus and ontologies can be used to demonstrate how closely the ontologies reflect the domain corpus [93]. Furthermore, the numerical analysis approach [94] can be utilized to assess the coverage, cohesion, and coupling of InPro for improved understanding [76].

Additionally, InPro is in its early stages, and there is potential for improvement through further implementation, problem-solving, and incorporating expert knowledge, as well as updating InPro documentation. Currently, it is a challenge for non-experts to identify which ontologies are appropriate in a particular domain and what the best practice is. Our research can be extended to model the operation of a smart factory by collaborating and integrating with existing organizations like IOF and AIOTI [95]. Another potential extension of our research is to formalize explicit and implicit if/then rules associated with renovation projects, using the Shapes Constraint Language (SHACL). Rule languages can be used in conjunction with ontologies to facilitate inference and data interpretation. These rules can be used to represent more intricate and precise relationships, such as linking constraints to activities based on their particularities. Moreover, we in the future would also explore collaboration between the manufacturing and construction industries. By linking with the DiCon ontologies, InPro could combine the information of the prefabrication production process with logistics and onsite construction process, to establish an integrated information system for advanced production and construction management.

7. Conclusion

This paper presents the industrial production workflow ontology (InPro) to support the information integration from the heterogeneous resources within the manufacturing context. It leveraged BFO as a top-level foundational ontology and reused terms from existing ontologies and semantic models while implementing the 5 M-based (manpower, machine, material, method, and measurement) methodology to generate its internal structure. Competency questions (CQs) were defined to derive the ontology's requirements, which InPro successfully answered. The evaluations further demonstrated that there are no taxonomy problems in InPro and confirmed its technical quality. The case study was conducted to validate its feasibility for system and information integration.

The proposed ontology, InPro, offers a comprehensive knowledge representation for the manufacturing domain. End-users can leverage this ontology to integrate information and knowledge from various industrial systems, like MES, ERP, WMS, and IoT data to optimize the production process, develop their own information systems, and organize information in a machine-readable format, thus enabling efficient retrieval of the required information.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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