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Context-aware workflow management for smart manufacturing: A literature review of semantic web-based approaches

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ABSTRACT

Smart Manufacturing Systems (SMS) are software systems that identify opportunities for automating manufacturing operations by using Internet of Things (IoT) devices and services connected to machines. An active challenge of SMS is to satisfy the ever-changing conditions of industries, supply networks, and customer needs. To operate effectively, SMS should be flexible enough to perform automatic or semi-automatic adjustments to manufacturing processes in response to unexpected changes, a feature called context awareness. Recent advances in interpreting context data in the semantic web have permitted SMS to understand the active situation of manufacturing processes. This paper presents a literature analysis of context-aware workflow management approaches in the smart manufacturing domain, with a particular focus on semantic web-based approaches published from 2015 to 2022. A Systematic Literature Review (SLR) methodology was applied to analyze the state-of-the-art via the PICOC method. The contributions of this work are (1) an SLR about context-aware workflow management for smart manufacturing systems focusing on semantic web-based approaches, (2) a systematic taxonomy to break down the approaches in conformity based on content and main workflow management function area, and (3) identification of opportunities for improvement in technical features such as context awareness, use case implementation, tools employed, licensing, security, and scalability. A novel architecture and components are also proposed to address the identified active challenges.

1. Introduction

The fourth industrial revolution, also known as Industry 4.0, represents a significant transformation in which information and communication technologies (ICT) are integrated with manufacturing operation systems [1]. Diverse computational technologies, such as big data analytics, cloud services, and the Internet of Things (IoT), are emerging and converging within manufacturing systems to create Smart Manufacturing Systems (SMS). SMS are flexible, self-reconfigurable systems that can perform automatic or semi-automatic adjustments to production processes in response to changing conditions [2].

Effectively managing and analyzing the data generated by SMS production processes is challenging and the need for orchestrated IoT services is growing [3]. Orchestration defines how a set of tasks or activities within a workflow should be executed to achieve a goal [4]. The goals of workflows can be to transform materials, provide services, or process information. In particular, the Workflow Management discipline oversees the design, execution, and monitoring of workflow recipes [5].

Workflow recipes can be formalized into business processes using standard-globally known notation languages such as BPMN (Business Process Modeling and Notation language), BPEL (Business Process Execution Language), YAWL (Yet Another Workflow Language) [6]. The management of these formal workflow recipes falls within the Business Process Management (BPM) discipline. BPM is a set of tools and techniques that reduce errors and costs. They are used to increase productivity in organizations in fields ranging from telecom, insurance, government, and banks, to manufacturing companies [7].

Orchestrating IoT services often introduces interoperability issues, as the differences in communication protocols and technologies used by the various IoT devices make communication more complex [8]. To respond to this challenge, researchers have employed semantic web technologies to facilitate effective communication between IoT devices across a network [9]. For instance, Mehdi et al. [10] presented a semantic web-based solution for the smart city domain. Their proposal aims to improve interoperability among heterogeneous IoT devices and services and can be applied to other domains.

Semantic web technologies have the ability to interpret contextual information and infer new knowledge, which can enhance the dynamic nature of workflows [11]. Providing SMS with

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semantic web technologies can turn a system into a context-aware system. Such systems are able to re-configure themselves, displaying cognitive behavior when exposed to changing situations [9]. Dynamic adaptations take place during workflow design and runtime due to context-awareness support. This greatly facilitates the management of service level agreements (SLA) and ensures improved service availability and reliability in response to consumer requirements [9].

Given the critical nature of these systems in the Industry 4.0 manufacturing context, a critical review of the state of the art would appear timely. Although a number of pertinent studies have been identified, no research has been found that focuses on studying semantic context-aware workflow management approaches for the smart manufacturing domain. For instance, Breslin et al. [12] (2010) presented a literature review on the semantic web and its implications in the Industry domain. However, their work was published over ten years ago and primarily focused on highlighting the benefits of the semantic web in the industry rather than surveying state-of-the-art solutions.

Pauwels et al. [13] (2017) reviewed the applications and use cases of semantic web technologies in the Architecture, Engineering, and Construction (AEC) domain. Their work compares state-of-the-art solutions and is timely. However, they do not include approaches that feature context-aware capabilities, rather they mention it as a general concept of what the semantic web can do with context data.

An in-depth survey of IoT-based service composition approaches was presented by Asghari et al. in [14] (2018). The authors provided a technical taxonomy to classify the approaches, with semantic web-based approaches included in the Data-oriented category. They also mentioned context awareness as a future challenge in the service composition field. However, only 14 semantic web-based approaches were analyzed, as the semantic web is presented as one of the various techniques to achieve service composition. Additionally, they did not identify how the context-aware feature enhances the various workflow management function areas.

Bazan and Estevez [15] (2021) analyzed the state-of-the-art in business process management for industry 4.0 with a focus on IoT and smart objects. This work also examined the incorporation of context awareness into the BPM domain to enhance the reaction of business processes in response to context changes. However, only 2 semantic web-based approaches were analyzed in their work.

Therefore, in this paper, we present a methodological literature review of semantic context-aware workflow management approaches for the smart manufacturing domain published between 2015 and 2022. Topics, techniques, and proposals not discussed in the above-mentioned studies are analyzed. Existing proposals in the field are surveyed to identify the tools and techniques in use, and opportunities for improvement. Based on these findings, a novel architecture is proposed to respond to the challenges identified. The overarching objective of this work is to assist researchers in acquiring a general understanding of the field.

This paper is organized as follows: Section 2 briefly explains the background concepts and the literature review methodology is outlined in Section 3. In Section 4 the selected studies are reviewed and organized by a technical taxonomy. This section also includes comparison tables to analyze the strengths and limitations of each approach. Section 5, analyzes the trends and gaps in the selected studies and addresses the research questions. Section 6 proposes a consolidated approach based on the identified gaps. Finally, the conclusions together with a proposal for future research are presented in Section 7.

2. Background

In this section, key concepts and definitions related to workflow management, context awareness, and the semantic web are described. This section serves as an introduction to the terminology used in the paper and furthers understanding of the concepts under discussion.

2.1. Workflow management

Workflow management is responsible for the analysis, modeling, and automation of orchestratable tasks [4]. While the discipline does not require software, Workflow Management Systems (WfMS) are often utilized for collaboration, automation, and tracking. These systems manage workflows including the design, execution, and monitoring phases [5].

As shown in Fig. 1 a typical WfMS must provide support in three functional areas: (1) Design-Time: Concerned with defining and modeling workflow processes and activities, (2) Run-Time: Related to interactions with human users and IT applications which typically are part of workflow processes and activities, and (3) Management: Composed of tools that manage workflow processes and sequence the activities of processes. This latter includes monitoring tools to identify and resolve workflow problems before they can adversely affect critical business processes [4].

Workflow recipes can be formalized into business processes using standardized notation languages that support the execution of microservices (REST services) in the form of actionable tasks. These notation languages include BPMN (Business Process Modeling and Notation language), BPEL (Business Process Execution Language), and YAWL (Yet Another Workflow Language). The management of these formalized recipes falls within the Business Process Management (BPM) discipline, which includes systems and notation languages to design, execute, and manage business processes.

2.1.1. Business Process Management (BPM)

The Object Management Group (OMG) defines BPM as *"A set of techniques for the continuous, iterative improvement of all the processes involved in running a business"* [7]. BPM techniques help reduce costs and mistakes and increase efficiency in enterprises from a variety of fields including manufacturing [7]. The modeling of business processes must be based on standard notation languages for WfMS to understand and interpret them. The number of available notation languages is vast, a full comparison can be found in [16]. The most commonly used in the BPM community are BPMN, BPEL, YAWL, and DMN (Decision Model and Notation), all of which are XML-based for the design of business processes. However, BPMN has become the standard for business process diagrams [17], and according to OMG, DMN is designed to work alongside BPMN [18].

Numerous systems can manage business processes written in different notation languages. A Business Process Management suite (BPMS) is a technological array of robust tools for the design, execution, and monitoring of business processes. Some popular open-source BPMS considered by Gartner in [19,20] are Camunda, Bonita, and Process Maker.

Workflows can be enhanced by enabling context-awareness capabilities, which can interpret context changes and perform subsequent adaptations. The following subsection explains the concept of Context-awareness with an architecture proposed by IBM for building autonomous systems. Then, the technologies available for mapping and processing IoT sensor data are presented.

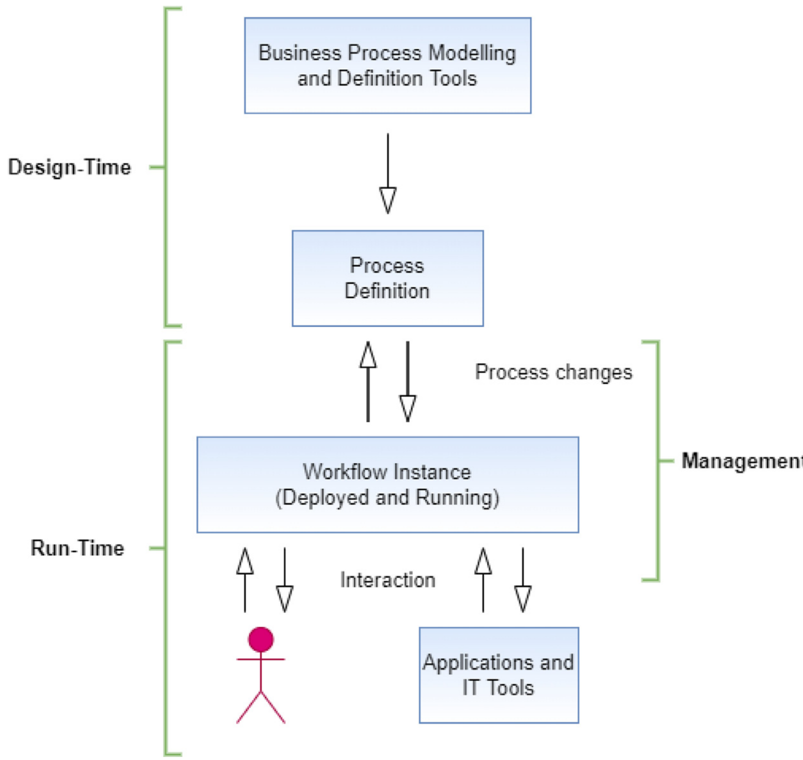

Fig. 1. Main function areas of a typical Workflow Management System.

2.2. Context-awareness

Context refers to any data that can be used to understand the current state (situational or locational) of an entity [21]. A system is considered context-aware if it can perform adaptations when changes occur in the environment in which it operates. These adaptations are tailored to user needs, preferences, and expectations [22]. Adaptations can be dynamic and applied during the system runtime. However, a context-aware system does not necessarily imply automation or real-time processing, rather it refers to the ability to respond to context [23].

Context-aware systems follow an architecture that supports adaptations based on environmental information [24]. IBM has proposed the MAPE-K (Monitor, Analyze, Plan, Execute, and Knowledge) framework for building autonomic and self-adaptive systems [25] (Fig. 2). MAPE-K establishes the basis for building components that can: (1) capture product and process information, (2) analyze this data to produce an output and store that information in a knowledge base, (3) formulate a plan to respond to any situation that may affect the normal behavior of a system, and (4) deploy that plan to allow adaptations to be applied in runtime.

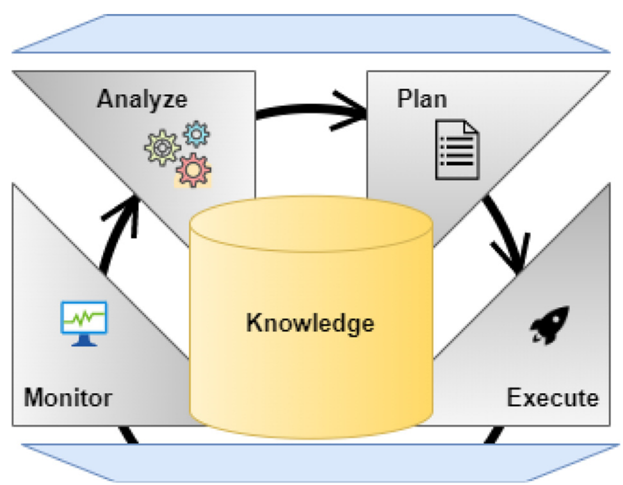

Fig. 2. IBM's MAPE-K reference model.
Source: Extended from [25].

Table 1 summarizes the MAPE-K modules together with techniques and technologies for executing each phase (based on [25]). Although, a wide variety of technologies are available for building context-aware systems, the Semantic Web is favored by the scientific community because it can model IoT sensor data into ontological entities and later apply inference techniques [26]. Thus, the next subsection explains the Semantic Web concept and its advantages.

2.2.1. The Semantic Web

The Semantic Web is a concept that gives information a well-defined meaning and enables computers and people to work in collaboration [27]. Semantic refers to the process of transforming data into ontological entities, ontologies are formal and standardized knowledge representations [27]. The semantic web technology stack includes: (1) OWL (Web Ontology Language)—the language for writing ontologies, (2) RDF (Resource Description Framework)—the language for writing data, (3) SWRL (Semantic Web Rule Language)-the language for writing rules or constraints, (4) SPARQL (Simple Protocol and RDF Query Language)—the language for querying RDF data, and (5) Semantic reasoners—engines that allow the interpretation of context and infer new knowledge by evaluating RDF data against SWRL rules [28].

The semantic Web allows structured and semi-structured data to be mixed, exposed, and shared across various applications. This linking structure of an ontology forms a labeled graph, where the edges represent named links between two resources, denoted by the graph nodes [29]. For instance, SOSA ontology is a model that

Table 1
Available techniques and technologies for each MAPE-K module.

MAPE-K module	Description	Technique/Technology
Monitor	Capture product and process information from IoT sensors.	Publish/Subscribe through OPC-UA, MQTT, Rest.
Analyze	Map/Model data into machine-understandable data.	Ontology Based Key-Value pairs Graph Based
Plan	Apply reasoning techniques to infer new information. The output is a plan that will respond to any situation that may affect the normal behavior of a system.	Machine Learning Semantic Reasoner Fuzzy Logic Decision tables Heuristics Mixed
Execute	Deploy the plan to allow adaptations at runtime.	Depends on the technologies used in both, the execution system and resulting plan.
Knowledge	Store analyzed and to be analyzed data and the resulting plan in a knowledge base.	Relational databases Graph databases Key–value storage Wide-column storage

describes IoT devices, sensors, and actuators, and models their properties and relationships [30]. The combination of IoT and semantic web technologies give rise to semantic interoperability, which is the ability to exchange and use information unambiguously between IoT entities [31]. There are numerous ontologies for capturing IoT devices, the most significant are SSN (Semantic Sensor Network),[1] which describes IoT sensors and their observations and IoT-Lite ontology,[2] which models knowledge about IoT systems and applications. Once IoT devices and their services are semantically annotated, context-awareness can be achieved in systems by applying inference capabilities to the semantic descriptions and constraints.

As IoT devices can capture diverse types of context information, context-awareness capabilities can be made available at design-time and/or runtime of workflow management areas. Furthermore, it is important to identify where and how the context-aware capability (empowered by semantic web technologies) has been implemented in each workflow management functional area and how it can be improved. To achieve this objective, the following section presents the protocol and method used for conducting this literature review.

3. Literature review methodology

The literature review was conducted following the guidelines for Systematic Literature Reviews (SLR) outlined in [32]. As illustrated in Fig. 3, the methodology consists of two main phases and associated sub-steps. The Planning phase involves defining the protocol, while executing the search string in the selected digital libraries and refining the selection of articles is carried out in the Conducting phase.

3.1. Planning

Defining the protocol is crucial in any SLR, as this outlines the procedures involved in the review and serves as a log of the activities to be carried out [33]. A number of tools can ensure the procedure is systematic, ranging from simple tools such as spreadsheets to specialized tools specifically designed for SLRs. In this regard, Parsifal is an open-source, online tool designed to support researchers perform SLRs, particularly in the context of Software Engineering [34]. Parsifal was chosen to document the entire process of this SLR.

Before commencing work, it is critical to define the scope. In this regard, the PICOC method is commonly used to identify the various components of a topic and to subsequently formulate research questions [35].

3.1.1. Define PICOC elements and synonyms

PICOC stands for Population, Intervention, Comparison, Outcomes, and Context. Table 2 details the definitions for each PICOC element together with the selected keywords and synonyms. As keywords are derived from the PICOC elements, it is essential to consider synonyms that can be used in queries performed in digital libraries.

3.1.2. Formulate research questions

Research Questions (RQs) are critical elements that determine the focus for study identification and data extraction [33]. RQs must include the PICOC elements to establish the research focus and assist in identifying the primary studies [35]. The research questions for this SLR are as follows.

(RQ1): What open perspectives and future challenges are associated with semantic web solutions that support the life cycle of business processes?

(RQ2): What tools and algorithms are used in building semantic web solutions to support the life cycle of business processes?

(RQ3): What evaluation factors are taken into consideration when measuring the performance of semantic web solutions that support the life cycle of business processes?

3.1.3. Select digital library sources

The validity of an article is dependent on the appropriate selection of the database as it must sufficiently cover the study area [36]. For instance, Web of Science (WoS) and Scopus are multidisciplinary databases that provide access to literature in technology, biomedicine, and other fields. However, in this work, it was important to also include sources relevant to computer science such as EI Compendex, IEEE, and ScienceDirect.

1 https://www.w3.org/TR/vocab-ssn/
2 https://www.w3.org/Submission/iot-lite/

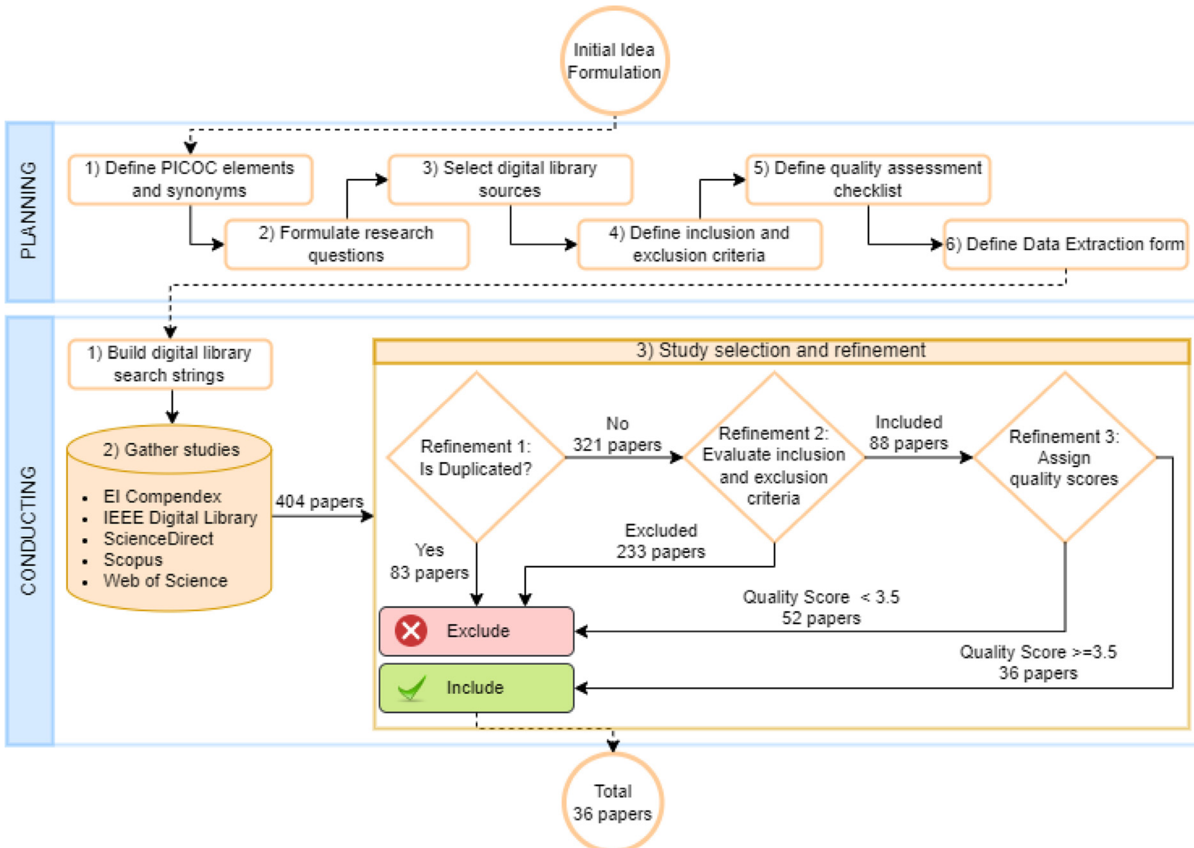

Fig. 3. Research methodology for this literature review.

Table 2
PICOC elements, keywords and synonyms.

PICOC	Description	Keyword	Synonyms
Population	The population in which the evidence is collected. The population can be a specific role, an application area, or an industry domain.	Industry 4.0	Digital Factory, Digital Manufacturing, Future Factory, Future Manufacturing, Industrie 4.0, Industry, Smart Factory, Smart Manufacturing
Intervention	Intervention is the methodology, tool, or technology that addresses a specific issue.	Process Modeling	BPEL, BPM, BPMN, Business Process Modeling, Business Process Modeling, YAWL
Comparison	Comparison is the methodology, tool, or technology in which the intervention is being compared.	Semantic Web	Ontology, Semantic, Semantic Web Service
Outcome	Outcomes relate to factors of importance to practitioners. The results that Intervention could produce.	Framework	Extension, Plugin, Tool
Context	The context in which the Comparison takes place. Some systematic reviews might choose to exclude this element.	Not applicable	Not applicable

3.1.4. Define inclusion and exclusion criteria

Inclusion and exclusion criteria are established to perform the refinement step for the articles collected from the library sources. Inclusion criteria refer to articles that can be considered for the next refinement step. Exclusion criteria refer to articles that do not fit this research purpose and are therefore removed from the study. Table 3 provides the inclusion and exclusion criteria considered for this SLR.

3.1.5. Define quality assessment checklist

A quality assessment checklist refers to a set of questions, answers, and scores assigned to each article. Consequently, articles can be sorted by their score and filtered to obtain those that are more closely related to the research domain. Table 4 sets out the quality assessment checklist for this SLR.

3.1.6. Define Data Extraction form

The Data Extraction form is a visual form composed of input text fields designed to register relevant data from the articles during the review process. This step aids in synthesizing the information from each article and answering the established research questions [37]. Table 5 lists the input fields of the data extraction form.

3.2. Conducting

After defining the protocol, the review is conducted by carrying out the previously defined steps.

3.2.1. Build digital library search strings

A search string was built by incorporating the PICOC elements and synonyms defined in 3.1.1 to run in each of the selected

Table 3
Inclusion and exclusion criteria.

Type	Criteria
Inclusion	• Strongly related: Abstract indicates that the full text is directly dedicated to Semantic workflows in the domain of Smart Manufacturing. • Partially related: Abstract indicates that some parts of the text are related to Semantic workflows.
Exclusion	• Article is duplicated in another database library • Article is not a journal article nor a conference paper • Article is not written in English • Article was published before 2015 • Semantics and workflows are only mentioned as an example or cited expression • The proposed solution uses semantics but not for workflows

Table 4
Quality assessment checklist.

Element	Description
Questions	• Does this article use semantic web technologies for the proposed solution? • Is this article related to workflows, dataflows, or any kind of business process modeling? • Is this article oriented towards industry (Smart Manufacturing)? • Does this article incorporate context awareness as part of the proposed solution? • Does this article propose a framework, tool, or methodology?
Answers	To assign a weight for each question answered. The weight is 1.0 if the answer is "YES", 0.5 if the answer is "Partially", and 0.0 if the answer is "No".
Cutoff score	The maximum score is 5, and the cutoff score is 3.5. Papers whose total score is less than the cutoff score are not considered for the deep review phase.

Table 5
Data extraction form fields.

Field name	Datatype	Value
Workflow Function Area	Select one	• Design-time • Runtime • Management
Main Focus	String field	n/a
Their identified problem	String field	n/a
Proposed solution	String field	n/a
Validation of proposed solution	String field	n/a
Their conclusion	String field	n/a
Identified Gaps/Comments	String field	n/a
Tools used for their proposal	String field	n/a
Open source	Boolean Field	Yes/No
Link to Source Code	String field	n/a

database libraries. The search string separates the population, intervention, comparison, and outcomes with parentheses and the Boolean operator AND, while the synonyms are separated with the Boolean operator OR.

```
("Industry 4.0" OR "Digital Factory" OR "Digital Manufacturing" OR "Future Factory" OR "Future Manufacturing" OR "Industrie 4.0" OR "Industry" OR "Smart Factory" OR "Smart Manufacturing") AND ("Process Modelling" OR "BPEL" OR "BPM" OR "BPMN" OR "Business Process Modeling" OR "Business Process Modelling" OR "Process Modeling" OR "YAWL") AND ("Semantic Web" OR "Ontology" OR "Semantic" OR "Semantic Web Service") AND ("Framework" OR "Extension" OR "Plugin" OR "Tool")
```

3.2.2. Gather studies

After executing the search strings in each digital library, the search results were downloaded as CSV (Comma Separated Value) files, which contain metadata such as abstract, author, title, year of publication, etc. This data is useful for data extraction and quantitative and qualitative analysis. During this step, a total of 404 papers were collected from all databases.

3.2.3. Study selection and refinement

This stage encompasses three steps for paper selection and refinement. The first step is to identify duplicates that appear in each of the searches in the selected databases. Automatic procedures are utilized to search and exclude duplicate papers by performing title matching. In this work, the studies were imported into Parsifal to utilize its pre-built functionality *Find_Duplicates*. The tool identified 83 duplicates from the initial 404 papers. The two remaining refinement steps were then executed manually by a single author for each article. Thus, filters with respect to the inclusion and exclusion criteria were applied to the remaining 321 papers during the second step. In the last refinement step, the 88 articles were assessed for quality, and weights/scores from 1.0 to 5.0 were assigned to each. As a result, 36 papers were scored >= 3.5 for quality and were selected for the deep review phase. Fig. 4 illustrates the distribution of imported, accepted, and rejected studies per digital library.

4. In-depth review of literature by categories

The 36 selected articles present approaches that use semantic web technologies in one or more workflow management functional areas. Table 6 categorizes the studies based on their main focus and workflow management functional areas. The categories include Process Modeling, Service Composition, Optimization of Service Composition, Reconfigurable Systems, Autonomous Computing, and Knowledge Management systems. Each category is described briefly, giving a general idea of the focus of the studies included in that category. The number of papers in each category is also listed.

The following sections review in depth the selected articles in each of the categories. Comparison tables are also provided for each category to briefly summarize the main ideas of each paper, use cases (if any), advantages, tools used, and opportunities. This latter highlights weaknesses within the proposals and helps determine current active challenges in this research domain. These active challenges are discussed in Section 5.

To identify the most significant works in each category, a citation analysis was conducted as shown in Fig. 5. This analysis measures the relevance of the articles by counting the number of times they have been cited by other works.

4.1. Process Modeling

Process Modeling is a discipline that supports organizational processes using different methods and techniques [38]. The Flow Chart model is a commonly used process modeling technique.

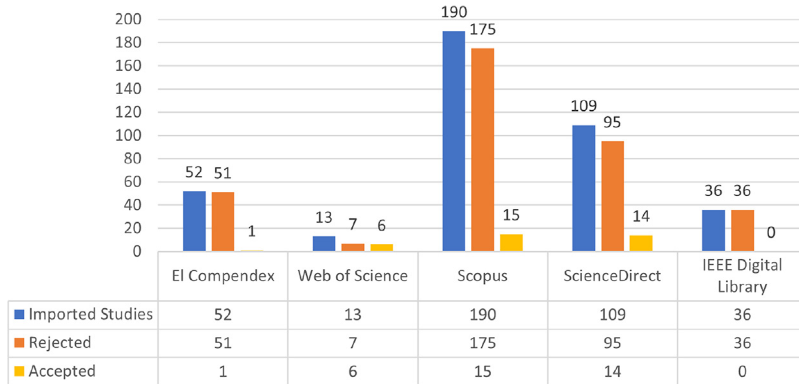

Fig. 4. Distribution of imported, accepted, and rejected studies per digital library.

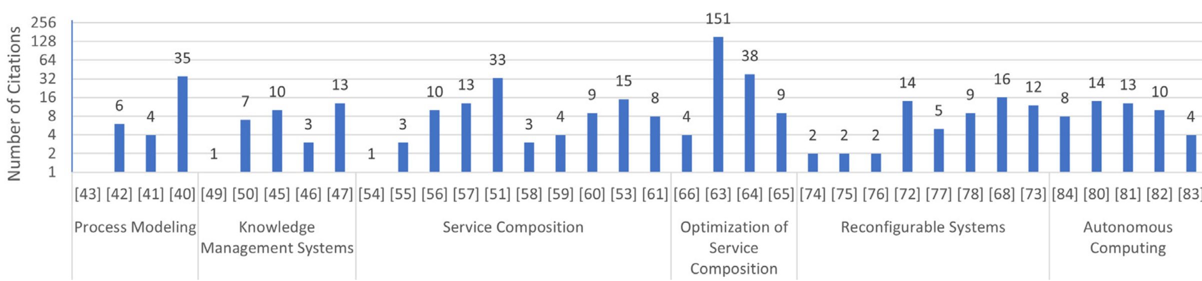

Fig. 5. Citation analysis of the selected studies.

Table 6
Categorization of selected studies.

Workflow function area	Category	Focus/Description	Papers
Design-Time	Process Modeling	Studies that focus on the modeling or design of workflow recipes as connected graphs (not necessarily executable).	**4**
	Service Composition	Studies that focus on the modeling or design of workflow recipes and service discovery and service selection for the final composition (should be executable).	**10**
Runtime	Optimization of Service Composition	Studies that focus on optimizing workflow recipes at runtime through service re-selection by evaluating Functional Parameters (FP) and Non-Functional Parameters (NFP), also known as Quality of Service (QoS) parameters.	**4**
	Reconfigurable Systems	Studies that focus on making substantial changes to the control flow through decision-making techniques to achieve the process goal (may require user intervention).	**8**
	Autonomous Computing	Studies that focus on automatic or dynamic re-composition, optimization, and execution of workflows without requiring user intervention.	**5**
Management	Knowledge Management Systems	Studies that focus on integrating a knowledge database to store semantics about devices and their services, to query, infer knowledge, and deliver that information to the user.	**5**

It is a graphical representation in which symbols are used to represent operations and flow directions for the definition and analysis of a business problem [39]. Table 7 compares the selected approaches categorized as Process Modeling. These studies propose prototypes and implementations that focus on the modeling of workflows enhanced by semantic web technologies. For instance, Suri et al. [40] proposed a semantic framework for the development of IoT-aware business processes. This approach integrates IoT resources into business processes using an extended version of BPMN 2.0. The approach uses Signavio BPMS to enable semantic annotations of the process model and IoT-BPO ontology to assist the user with ontology annotation.

An approach that utilizes BPMN and ontologies for automatic data processing in gas turbine maintenance was presented by Barz et al. in [41]. The architecture processes semantically annotated data from machines to sensors and analyses data for anomaly detection. This approach employs a semantic knowledge base to store and query data and Camunda BPMN to design and control the process of gas turbine maintenance. Similarly, Kaar et al. [42] developed an ontology that integrates characteristics of the multi-perspective RAMI 4.0 (Reference Architectural Model for Industry 4.0) and proposes combining it with S-BPM (Subject-oriented Business Process Management) to encapsulate industry standards and stakeholder behavior.

4.2. Knowledge-Management Systems

The main purpose of Knowledge-Management Systems is to capture product and process information and later use it to automate processes. These systems typically store information in a knowledge database, and then infer new knowledge by applying complex rules, heuristics, artificial intelligence, and agents [44]. Table 8 compares the selected approaches categorized as Knowledge Management Systems. These studies propose prototypes

Table 7
Comparison of process modeling approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[43]	A semantic business process modeling approach.	–	BPMN compliant	Need for prototype and experimental phase	• CODO • DOLCE • BPMNO
[42]	A RAMI 4.0-based ontology	–	RAMI 4.0 and S-BPM compliant	Need for prototype and experimental phase	• RAMI 4.0 • S-BPM • C-MAPS tools
[41]	An architecture for machine anomaly detection using a digital technique for filling reports and handwriting recognition.	Siemens gas turbine maintenance	• Automation upgrade • Complexity abstraction	Need for security	• Camunda BPMS • BPMN • MyScript • Blazegraph
[40]	A framework to support the development of IoT-aware business processes.	Monitoring the temperature of orchids	Complexity abstraction	Need for fault-tolerance	• Signavio BPMS • IoT-Lite • BPMN

Table 8
Comparison of knowledge-management systems approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[48,49]	A semantic wiki-based system.	Austempered Ductile Iron	Open-source	Need for an API	Loki semantic wiki
[50]	A knowledge base for optimizing engineering processes.	Engineering of robot-based automation solutions at a German automotive supplier	Complexity abstraction	Complex to maintain	• Microsoft Excel • VBA programming language
[45]	An ontology and knowledge base for computing energy efficiency indicators.	A welded hull panel assembly	Inference capabilities	• Need for real-time data • Need for UI to deliver results	• Protégé • RacerPro • Bonita BPM
[46]	A framework to support the development of context-aware IoT applications.	Smart home	• Complexity abstraction • Customizable services • API • Context-awareness	-	-
[47]	An API to obtain the semantics of devices.	Energy management systems for decision support	Complexity abstraction	Need for security	• Java, JAX-RS, JAXB, OWL2, SPARQL, GraphDB • RDF/XML Validator, OWL Validator, TopBraid Composer

and implementations that integrate knowledge databases in systems to store and process the semantics of devices and services. For instance, Borsato [45] proposed a semantic information model based on an ontology for the calculation of energy efficiency indicators. A BPMN is first created and then divided into activities until the elementary tasks are reached (top-down approach) so that all BPMN entities can be mapped into the ontology as individuals and assertions. Then, the inference and query capabilities of Protégé and RacerPro are employed. Each task is accomplished by an operation, which corresponds to a manufacturing unit process. Their solution provides parameters to a manufacturing unit process by bringing data property assertions for a given individual.

A semantic and context-aware framework for the smart home scenario is presented by Elkady et al. in [46]. The framework gathers data from IoT devices and employs ontologies to interpret context, considering diverse types of context data such as temperature, location, date, and time. An API (Application Programming Interface) provides abstract access to the backend and also delivers contextual information. The results show that their approach can make predictions based on context changes. Similarly, Hippolyte et al. [47] proposed a semantic and context-aware framework for the energy management field. Ontologies are employed to describe the semantics of devices, and a web service generator tool creates web services from instances of the ontology. The tool embeds SPARQL queries and an API is used to facilitate data extraction from the knowledge base with HTTP/REST instead of HTTP/SPARQL.

4.3. Service composition

Service composition is a technique that involves the discovery, selection, and execution of services to achieve a user goal. This is performed by breaking down the user goal into functional and non-functional requirements/properties (FPs and NFPs) [14]. Table 9 compares the selected approaches categorized as Service Composition. These studies propose prototypes and implementations that focus on the composition of services using semantic web technologies. For instance, Bucchiarone et al. [51] proposed an AI (Automated artificial intelligence) planning-based composition framework. This framework enables service discovery, selection, composition, and deployment by using an extension of BPEL in what [52] called *"Adaptable Pervasive Flow Language (APFL)"*. Using APFL activities can be annotated with preconditions and effects at design time. The authors used APFL to create a composition planner module that performs service composition. The algorithm creates abstract activities that are then replaced by "fragments", which are smaller compositions. An AI planning algorithm is employed as the reasoning mechanism to minimize the search space by considering knowledge from previous executions and analyzing context for the reuse of fragments in the final composition.

Kir and Erdogan [53] designed an intelligent business process management framework called "agileBPM". This framework combines ontologies and agents to provide cognitive and exception-handling capabilities by using the Hierarchical Task Network

Table 9
Comparison of service composition approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[54] [55] [56]	An architecture for semantic service annotation.	• Aluminum forging for bicycle hull body forming • Preventive maintenance	• Robust architecture • Service marketplace • Complexity abstraction • BPMN compliant • Open-source	• Complex to set-up • Need to read sensor logs	• OWL-S • Docker • Java • BPMN
[57]	A hybrid composition framework (top-down and bottom-up).	BPEL compliant	• Open-source • Interactive UI	Need to handle NFPs	• BPMN to BPEL library • Petals BPM, EasierSBS, XPath language, SAWSDL
[51]	An AI planning-based composition framework.	Process chain of the car logistics	• Context-awareness • Interactive UI	Need for security	• BPEL, ASTRO CAptEvo framework • AI planning algorithm as the reasoning mechanism
[58]	Location-aware discovery mechanism for the IoT.	A personal assistant that recruits services based on their location.	Interactive UI	• Need to handle location change scenarios • Need to capture GPS coordinates	• Schema.org, Protégé, Hydra vocabulary, JSON-LD • Phyton, rdflib, rdflib_jsonld, Elixir, Apache Jena Fuseki
[59]	A semantic Node-RED version.	FESTO Process Automation Workstation	• Complexity abstraction • Open-source • Interactive UI	Need for security	• Node-RED • iot.schema.org, JSON-LD, SPARQL
[60]	An ecosystem for the discovery and composition of IoT.	Smart city	• Open-source • Robust architecture • Security	–	• O-MI, O-DF, Schema.org, MobiVoc • SQL, NoSQL • OAuth, OpenID, SAML, LDAP, JWT
[53]	A BPM framework that combines ontologies and agent-based process execution to provide decision-making capabilities.	–	• Context-awareness • Open-source • Fault-tolerant	Need for security	• BPMO, Enterprise Strategy Ontology • SWRL, WSMO, OWL-S, OWLS-TC4 • HTN Planner, Wade platform
[61]	A framework for the modeling and execution of IoT business processes without changing the meta-model of BPMN.	–	• Context-awareness • Open-source • BPMN compliant • Microservice-oriented architecture	Need for security	• SOSA ontology, SWRL, protege, SPARQL • BPMN, API, Camunda, Java, .Net

(HTN) planner algorithm to compose services. The algorithm evaluates QoS, business goals, and business rules to perform a search and ranking of the processes that can achieve the user goal. Similarly, Mazzola et al. in their studies [54–56] proposed an architecture and components for semantic web service composition. This approach uses a web service annotation tool that follows the Everything-as-a-Service principle to annotate web services and store them in a common marketplace. BPMN models are created and enriched with annotations to define the semantic behavior of each task in terms of IOPE (Input, Output, Preconditions, and Effects). A pattern-based algorithm is used for the semantic composition of business processes and an optimization phase is included to consider non-functional aspects (QoS constraints) for solving the Constraint Optimization Problem (COP).

4.4. Optimization of Service Composition

The Optimization of Service Composition is the process of re-selecting services within an existing composition to improve the Quality of Service (QoS) parameters in accordance with Service Level Agreements (SLA). This process is driven by the convergence of a large number of web services that perform the same function [62]. QoS parameters are non-functional properties (NFPs) that are used to evaluate services and determine the optimal service for a task. These parameters are represented by numeric values from 0 to 100, such as response time, availability, throughput, success rate, reliability, compliance, best practices, latency, relevancy, and class (highest, lowest, platinum, gold). Table 10 compares the selected approaches categorized as Optimization of Service Composition. For instance, Baker et al. [63] developed an optimal service composition algorithm specialized in energy efficiency. The algorithm focuses on reducing the number of services used in the composition problem, which also results in a reduction in energy consumption. The approach incorporates semantic web technologies to describe services. An initial composition plan is created by considering various services from different providers. The algorithm then performs optimization by ordering the list of service providers such that those with the largest number of services are placed first. The optimum individual service or composite service is then selected considering QoS conditions. Finally, the re-composition is performed by taking the optimal services.

An optimal semantic web service composition approach was presented by Bekkouche et al. in [64]. Their approach takes into account NFPs and QoS constraints for the optimization problem, which is solved by applying the Harmony Search (HS) algorithm. The approach is tested using the Web Service Challenge (WSC) 2009 dataset. Similarly, Abid et al. [65] proposed an optimal semantic web service composition framework that first classifies, discovers, and composes services. Optimization is then performed by using semantic similarity measures, considering FPs and QoS parameters to calculate the optimal services.

Table 10
Comparison of optimization of service composition approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[66]	Optimization based on FPs and NFPs in design-time and runtime by using the COP algorithm.	• Aluminum forging for bicycle hull body forming • Preventive maintenance	• BPMN compliant • Open-source	-	• antlr, JaCoP solver, OWL-S • BPMN • COP algorithm
[63]	Reducing the number of services for the composition problem can turn in a reduction in energy consumption.	-	-	Need to consider more evaluation factors such as memory, CPU, size of data sent and received, and execution time.	• OWL-S XPlan package • Java, NetBeans
[64]	Optimization based on NFPs and QoS constraints by using the Harmony search algorithm.	-	Considers a well set of QoS attributes: Response time, cost, availability, reliability, and reputation.	Need to standardize the recipe using notation languages	• Harmony search algorithm • WSC 2009 dataset
[65]	Optimization based on FPs and NFPs by using semantic similarity measures.	-	-	Need to standardize the recipe using notation languages	• Java, Jena, and JAXP • OWL-S, SWS Test Collection

4.5. Reconfigurable Systems

A Reconfigurable System is a system that can perform reconfigurations dynamically at runtime by rearranging elements such as applications, platforms, system architectures, underlying infrastructures, and management facilities. This is typically conducted during system maintenance or when a new update is installed, sometimes requiring user intervention [67]. Table 11 compares the selected approaches categorized as Reconfigurable Systems. These studies propose prototypes and implementations that focus on reconfiguring systems to make substantial changes to the control flow with the aim of achieving user goals through decision-making, adaptive case management, and machine-learning techniques. For instance, Ciasullo et al. [68] presented a framework to support group decision-making problems in the context of business process outsourcing by selecting the most suitable provider. The framework includes a "time-aware" feature to consider the time elapsed from past executions. The framework relies on the fuzzy linguistic consensus model (presented in [69,70]) and a context-aware plugin (presented in [71]). A reinforcement learning algorithm is implemented to learn and assign weights/scores to support the users in the decision-making process, by considering the current context and the time at which they take part in the decision-making group.

A context-aware BPM ecosystem is proposed by Song et al. in [72]. This proposal integrates IoT data into context ontologies to enhance business process decision-making. Using the framework, business processes are aware of their context at both design time and runtime and thus can adapt to dynamic situations. The architecture consists of business process models and contextual entities including their relationships. Context is sensed from a variety of sources including IoT devices and information systems, and then analyzed to output understandable contextual knowledge. Decision models are then created to take this contextual knowledge into account. For the execution phase, the business processes and decision models are deployed and executed accordingly. In a similar vein, Ordoñez et al. [73] developed a framework for automating monitoring and decision support. The framework employs Natural Language Processing (NLP) for the creation of a "problem file" which defines a sequence of actions to achieve a goal. A monitoring module gathers logs generated during execution. A decision support module then takes the logs and determines whether there are real errors or not, by using an inference engine to change the service in charge if needed.

4.6. Autonomous Computing

Autonomous Computing is a research area that focuses on self-adaptive and autonomic computing systems, which are able to configure, heal, optimize, and protect themselves without the need for human intervention [79]. Table 12 compares the selected approaches categorized as Autonomous Computing, which focus on the automatic or dynamic composition, optimization, and execution of services. For instance, Alférez and Pelechano [80] proposed a context-aware framework for the autonomic adjustment of service compositions at runtime. The approach creates models at design time using ontologies and BPMN and WS-BPEL to support dynamic adjustments of service composition. A verification phase checks the changeability of the models and their configurations before the execution to ensure safe service re-composition. At runtime, whenever a context event happens, the previously created models are queried to perform service re-composition.

An approach to autonomous computing by applying the MAPE-K (Monitor, Analyze, Plan, Execute, and Knowledge) paradigm was designed by Lam et al. in [81,82]. This approach relies on an "Autonomic Manager" that facilitates the development of interoperable IoT systems using semantics web Technologies. The "Autonomic Orchestration" uses the semantics of the "Autonomic Manager" to enable the dynamic orchestration of services within Arrowhead Framework.[3] The architecture integrates a Semantic Extractor (SE) that gathers information from services and systems and transforms them into semantic knowledge. The SE uses Machine Learning (ML) techniques to recognize popular semantic models and extract the necessary information. A knowledge graph is then built from the chosen ontologies and the information is stored in a knowledge base. An Autonomic Framework (AF) employs SPARQL and SWRL as reasoning mechanisms for knowledge inference and decision-making at runtime.

Arul et al. [83] proposed a framework for automatic and dynamic service composition by adding semantics to web services to satisfy the dynamic changes of user needs. They adopted an extended version of the hierarchical task network (HTN) planner, named hierarchical task network based on user constraints (HTNUC) which can understand OWL-S processes. This proposal takes user requirements and constraints to produce an abstract composite workflow that determines the execution order of tasks. An optimal abstract composite workflow is then created to satisfy

3 https://www.arrowhead.eu/

Table 11
Comparison of reconfigurable systems approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[74]	An ontology for reconfigurable system integration and decision-making support.	Festo test bench	-	-	• PPRR ontology • GATE RDF editor, RDF, SPARQL
[75]	An ontology for ACM systems that allows business partners to describe business cases using natural language.	Approve an architectural model	Adaptations are immediately available to the business users	Requires coordination between business users	Papyrus Converse
[76]	A context manager module to decide whether a service should be kept, tuned, or changed on the fly.	A car-seat example picked from a FabLab	• Considers FPs and NFPs, the inputs, and outputs of services • Context-awareness • On-the-fly service replacement	Re-composition phase still needs development	• Java, Jena API, IntelliJ IDEA • Ontologies: SSN, FIPA CSIRO, SDO
[72]	A context-aware BPM framework for making adaptations in dynamic situations.	Truck pick-up cargo	BPMN and DMN compliant	Need for a standard architecture	• OWL, SWRL • DMN
[77]	An assistant for engineering change processes.	A product service system engineering process	WS-BPEL compliant	• Complex to maintain • Low scalability • Need for security	• .Net framework • Goal-oriented process modeling language (GRL)
[78]	A decision support system based on the "Ant Colony Optimization" algorithm.	• Place order in wholesale of food • Manufacture of chocolate	BPMN compliant	Need for security	• Business Field Ontology, Collaborative ontology • Java, Neo4j, Ant Colony Optimization
[68]	A context-aware framework for group decision-making in business process outsourcing.	Decision-making on who to outsource the production sub-process of an Italian footwear company.	Context-awareness	Need to consider more context-awareness properties	• Fuzzy linguistic consensus model • Reinforcement learning algorithm • OWL2, SKOS
[73]	A monitoring and decision support module to determine whether a service should be replaced.	-	Considers error logs	Need for security	• Natural Language Processing, AI planning • Java, JSLEE, ITIL • SOA Ontology, OWL, OWL-API, SWRL, Pellet reasoner

the user goals. Ontology-based search is employed to convert syntactic to semantic definitions of services. Finally, the most suitable service candidates are selected using semantic web service discovery (SWSD) to produce a concrete-executable workflow from the discovered services.

5. Discussion

In this section, the trends and gaps of the state-of-the-art studies are analyzed and the research questions are addressed.

5.1. Analysis and answers to RQs

(**RQ1**): **What open perspectives and future challenges are associated with semantic web solutions that support the life cycle of business processes?**

(a) Need for standardization in process modeling and service-oriented architecture solutions

Many of the reviewed papers propose incorporating new process modeling languages to make a recipe interpretable for semantic reasoners and workflow management software. While [85] demonstrated that existing process modeling languages such as BPMN and BPEL can support additional features and customized elements and attributes, it is important to maintain the high level of expressiveness in existing notation languages, as outlined in [61].

In terms of standardization in service-oriented architectures, many of the prototypes reviewed are presented as non-industrial-oriented architectures, lacking support for important features such as security and scalability. A solution that follows a service-oriented architecture (SOA) offers several advantages, including scalability, integration, wider reach, and future-ready, as outlined in [86]. This can be achieved by making connections to the backend through APIs [87]. Industrial IoT frameworks should feature SOA, automation, scalability, and security as for example Arrowhead Framework [88], AUTOSAR [89], and FIWARE [90]. A comparison of recent platforms and state-of-the-art of industrial IoT frameworks can be found in [91].

RAMI 4.0 was introduced to standardize interoperability between machines. This model standardizes and digitally represents I4.0 components through a three-dimensional layer model [92]. To achieve this, the concept of an Asset Administration Shell (AAS) is introduced, which enables interoperation and identification of assets within the network by providing their technical and operational data. More details about AAS can be found in [93].

(b) Need to assist process designers in the modeling of manufacturing business processes

In the context of BPM, the design of business processes is a task handled by process designers. Often BPM is applied to systems in the domain of Banking, Enterprise Resource Planning, or similar management software [94]. However, some authors in the literature have found the need to include process designers in the domain of manufacturing systems for the design of manufacturing business processes. Business process designers often do not

Table 12
Comparison of autonomous computing approaches.

Ref.	Main idea	Use case	Advantage	Opportunity	Tools used
[84]	A semantic engine for the dynamic execution of business processes.	Create Order business process	Context-awareness	-	• PrjOnt, SWRL rules • WSO2 application server • Activiti
[80]	A context-aware framework for the autonomic adjustment of service compositions at runtime.	-	Context-awareness	• Needs to consider more context-awareness properties. • Needs a revalidation step to ensure that a service is actually unavailable.	• Goal/ Question/ Metric (GQM), MAPE-K paradigm • FAMA-FW, GNU Prolog, BPMN, WS-BPEL • Java, Java VisualVM, Apache Axis2, Apache Tomcat, Apache ODE
[81,82]	An autonomous computing framework using the MAPE-K paradigm for dynamic orchestration of services within the Arrowhead Framework.	Smart home	• Arrowhead compliant • Security (handled by Arrowhead Framework)	Needs to support human intervention for execution confirmation	• MAPE-K paradigm, Machine Learning techniques • IoT-O, Semantic Sensor Network (SSN), Semantic Actuator Network (SAN), SPARQL, SWRL, RDF, OWL
[83]	A framework for automatic and dynamic service composition adding semantics to web services and satisfying the dynamic changes of user needs.	Finding the most suitable composite solution	Context-awareness	Need for security	• HTN planner • OWL-S, WSMO, OWL-API, Pellet reasoner • Extended Finite-State Automaton (EFA), WSC 2009 dataset

possess the appropriate knowledge or tools to configure machine services or orchestrate processes using such services. Therefore, the challenge lies in providing tools to aid process designers in the design of manufacturing business processes. Considering that AAS describes machine services by using submodels [92], an AAS-based modeling tool can be developed offering asset services in the modeler palette, thereby facilitating the design of manufacturing business processes.

(c) Need for business process management software that can take advantage of the edge computing environment

Most existing prototypes for service compositions are delivered as cloud-based architectures, with data processing mainly handled in a central server. However, edge computing has become a popular paradigm in the industrial domain, as it delivers low latency, more mobility, and more contextual information by connecting cloud computing facilities to end-users [59]. Therefore, it is crucial to develop business process management software that can compose services in the edge environment.

(d) Need to interpret contextual information to perform dynamic adaptations

This literature review analyzed studies in which the context-awareness feature was present in 16 out of 36 proposals. Context-awareness is an important characteristic of ubiquitous computing as it permits the interpretation of contextual information [95]. In a workflow instance, context-awareness can be achieved by capturing data from devices and processing it through the use of semantic web technologies [96]. Fig. 6 illustrates the application of context-awareness by workflow function area. For instance, in the design-time phase, IOPE is the main technique for enhancing workflow design. This was demonstrated in the work of Bucchiarone et al. [51], which achieved semi-automatic workflow modeling. In the runtime phase, optimization based on Quality of Service (QoS) is the main technique, as reported by Bekkouche et al. in [64] who replaced services within workflows at runtime. Knowledge management using semantic wikis is the most common technique in the management phase. In this regard, Elkady et al. [46] proposed a semantic-based framework that delivers context information to the user interface in the form of reminders or notifications triggered by context changes.

Although some authors enabled context-awareness in their proposals, this should be further leveraged by considering sensor logs. As described in Section 2.2.1, data delivered by sensors can be exploited using ontologies. Attributes of ontologies that can interpret contextual information include `responseTime`, `gpsPosition`, `successRate`, `networkLatency`, `hasWeight`, `hasSize`, `hasTemperature`, and `hasHumidity`.

To effectively adapt to unexpected events during the execution of tasks, it is crucial to gather and analyze data in real-time to create a plan. One approach is IBM's MAPE-K reference model for building autonomous systems, as outlined in Section 2.2. In the monitoring phase, IoT sensors can be utilized to capture context data, which can then be processed through semantic web technologies such as OWL, RDF, SWRL, and SPARQL. During the planning phase, decision tables can be created using the Decision Model and Notation (DMN) standard. By combining DMN with BPMN, the workflow execution can be dynamically altered to ensure standardized decision-making.

(RQ2): What tools and algorithms are used in building semantic web solutions to support the life cycle of business processes?

The reviewed studies proposed prototypes and implementations that are built on top of semantic web technologies to support the stages of the workflow life cycle. Table 13 summarizes the semantic web tools employed to develop each of the proposals. The complete list of the tools and ontologies can be found in the tables published in Section 4, organized by category.

(RQ3): What evaluation factors are taken into consideration when measuring the performance of semantic web solutions that support the life cycle of business processes?

To answer this question, the datasets and measurement variables that the articles under review employed for the experimental phase of the proposals were collected. Of the 36 reviewed studies, 30 presented evaluation phases of the proposals. Fig. 7 shows the top 5 measurement variables employed to measure the performance of their approaches. *Execution Time* scored the highest and was considered in 12 papers, followed by *Precision/ Recall/*

Table 13
Tools and techniques.

Domain	Description	Tools
Ontology	Defines and models sensors, services, the data they gather, and their domain.	• SSN • SOSA • OWL-S • IoT-O • SOA Ontology • Schema.org
Semantic reasoners	Computes context data and infers new knowledge.	• RacerPro • Hermit • Pellet
Other reasoners		• AI Planning • Harmony Search • Ant Colony Optimization • Constraint Optimization Problem
Semantic Graph Database	Integrates heterogeneous data from many sources and creates links between datasets.	• GraphDB • SPARQL • SWRL
Workflow Management	Includes tools for workflow design, execution, and monitoring.	• Camunda • Signavio • Bonita • Activiti

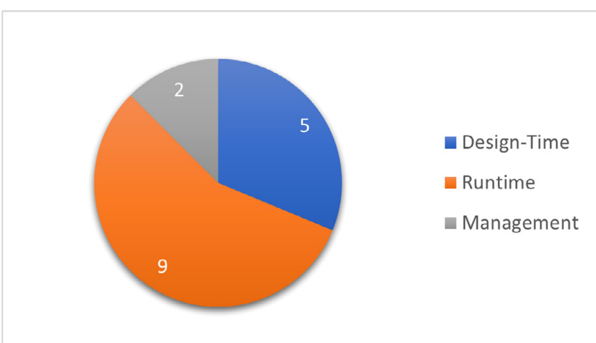

Fig. 6. Distribution of context-awareness feature by workflow function area.

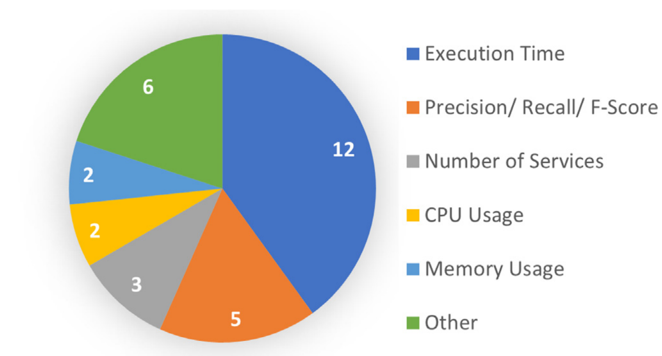

Fig. 7. Distribution of measurement variables employed in the articles under review to evaluate the proposals.

F-Score with 5, and *Number of Services* with 3. *Precision/ Recall/ F-Score* are performance metrics (between 0 and 1) often related to classification methods. The authors under review applied these metrics to evaluate the quality and quantity of the data retrieved from collections. A higher *precision* indicates that an algorithm returns more relevant results than irrelevant ones, and a higher *recall* means that an algorithm returns most of the relevant results (irregardless of whether irrelevant results are also returned). *F-Score* provides a single score that balances both the concerns of *precision* and *recall* in one number. On the other hand, context-aware variables were not evaluated: `response time`, `location`, `availability`, `throughput`, `success rate`, `reliability`, `compliance`, `best practices`, `latency`, `relevancy`, and `class`.

Fig. 8 summarizes the use cases that the authors considered for testing their proposals. For instance, in the use case "Truck pick-up cargo", Song et al. experimented with a context-aware BPM framework for making adaptations in dynamic situations. In the case of "Manufacture of chocolate", Montarnal et al. proposed and tested a decision support system.

With respect to data, Table 14 lists the datasets utilized by the authors for the evaluation phase. These are collections of semantic web services that include QoS parameters.

A keyword correlation analysis is presented in the next section, which explores the topics of study in the reviewed paper.

5.2. Analysis of keyword correlation

This subsection reveals topics of study in this literature review. VOSviewer,[4] software widely used in the scientific community for constructing and visualizing bibliometric networks as cluster maps, was employed. A comparison of VOSviewer and CitNetExplorer and the description of the clustering algorithms can be found in [97]. For this analysis, VOSviewer was fed with a dataset of indexed keywords of the papers that passed the 2nd refinement phase (88 papers) (Sub- Section 3.2.3). The data was manually polished to remove extra white spaces and then exported to a CSV file to serve as input for the software.

In VOSviewer, each circle represents a keyword, and the size of the circle indicates the number of papers that contain that keyword in their title or abstract. Keywords that frequently co-occur tend to be located close to each other in the visualization, and lines represent the links between keywords with a minimum strength of 1. As shown in Fig. 9, the most prominent theme in the literature is *ontology*, represented by the blue cluster of 22 items. This is followed by the combination of *internet of things* and *semantic web*, represented by the orange cluster of 19 items. On the other hand, *edge computing* and *semantic interoperability*

4 https://www.vosviewer.com/

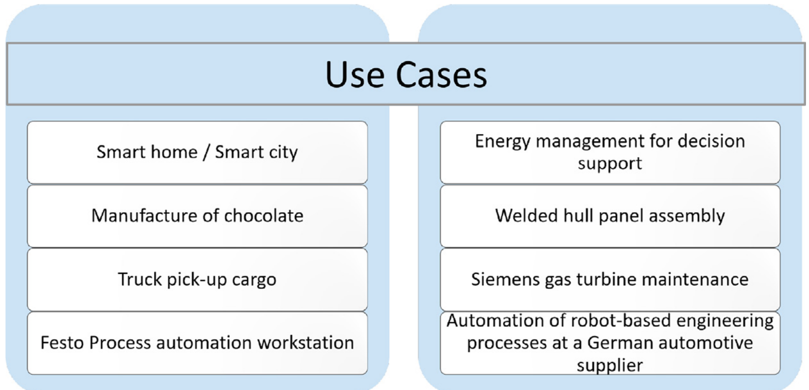

Fig. 8. Use cases employed in evaluating the proposals under review.

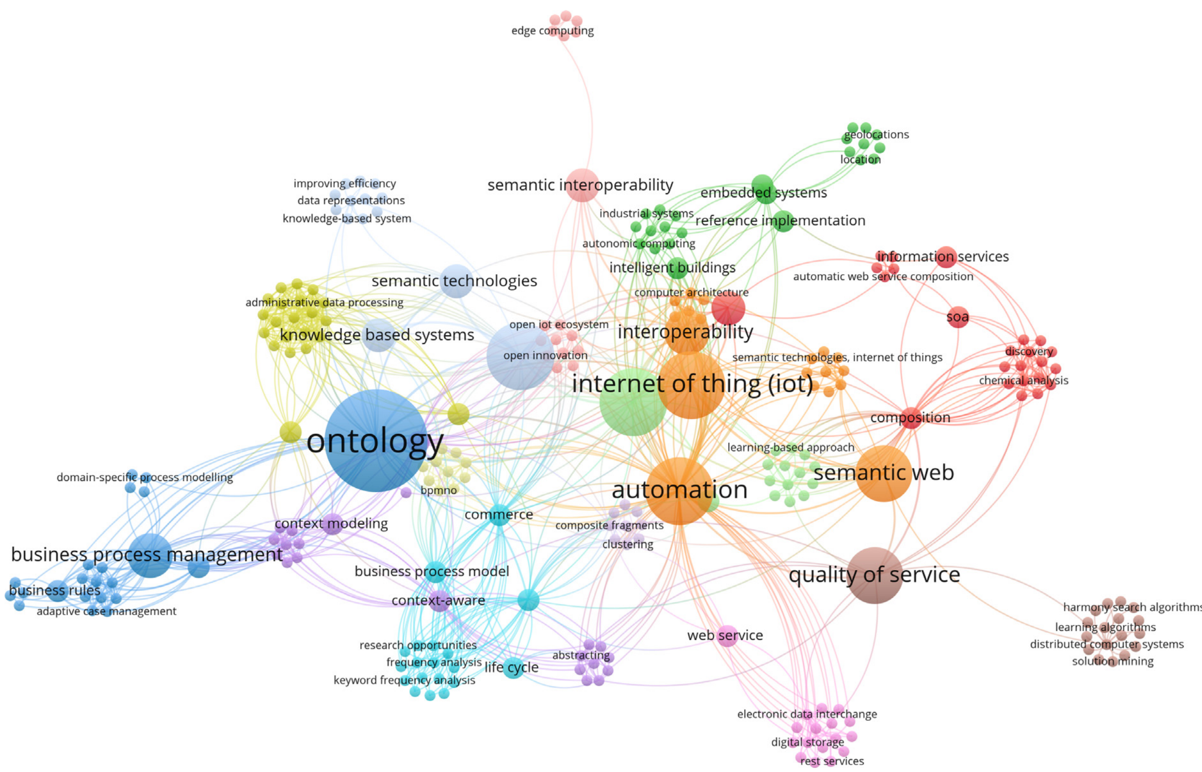

Fig. 9. Analysis of keyword correlation.

Table 14
Datasets employed for the experimental phase.

Proposal	Dataset	Link
[46]	Aruba dataset	http://casas.wsu.edu/datasets/
[64,83]	WSC 2009 dataset	http://www.wschallenge.org/
[65]	SWS Test Collection[a]	https://github.com/kmi/sws-test-collections
[53]	OWLS-TC4	http://projects.semwebcentral.org/projects/owls-tc/
[63]	OWL-S XPlan package dataset	https://www.dfki.de/klusch/owls-xplan/OWLS-XPlan-1-Manual.pdf
[57]	SAWSDL test collection	http://projects.semwebcentral.org/projects/sawsdl-tc/

[a]A GitHub repository with shared resources for testing semantic web services technologies that contain most of the other mentioned datasets.

(top center, in pink), is the smallest cluster with only 7 items and limited connections to larger clusters. In addition, no direct link appears to exist between *edge computing* and *business process management*, which suggests a potential research opportunity in this area.

In summary, the current tools and algorithms used for creating semantic and context-aware smart manufacturing solutions have been identified. Workflow management systems are particularly utilized to manage manufacturing processes, with BPMN as the standard notation language. Semantic web technologies have reached maturity level, with respect to ontologies for describing machines, devices, and services. Nevertheless, this literature review reveals a lack of prototypes that incorporate Industry 4.0 standard architectures such as AAS. In the following section,

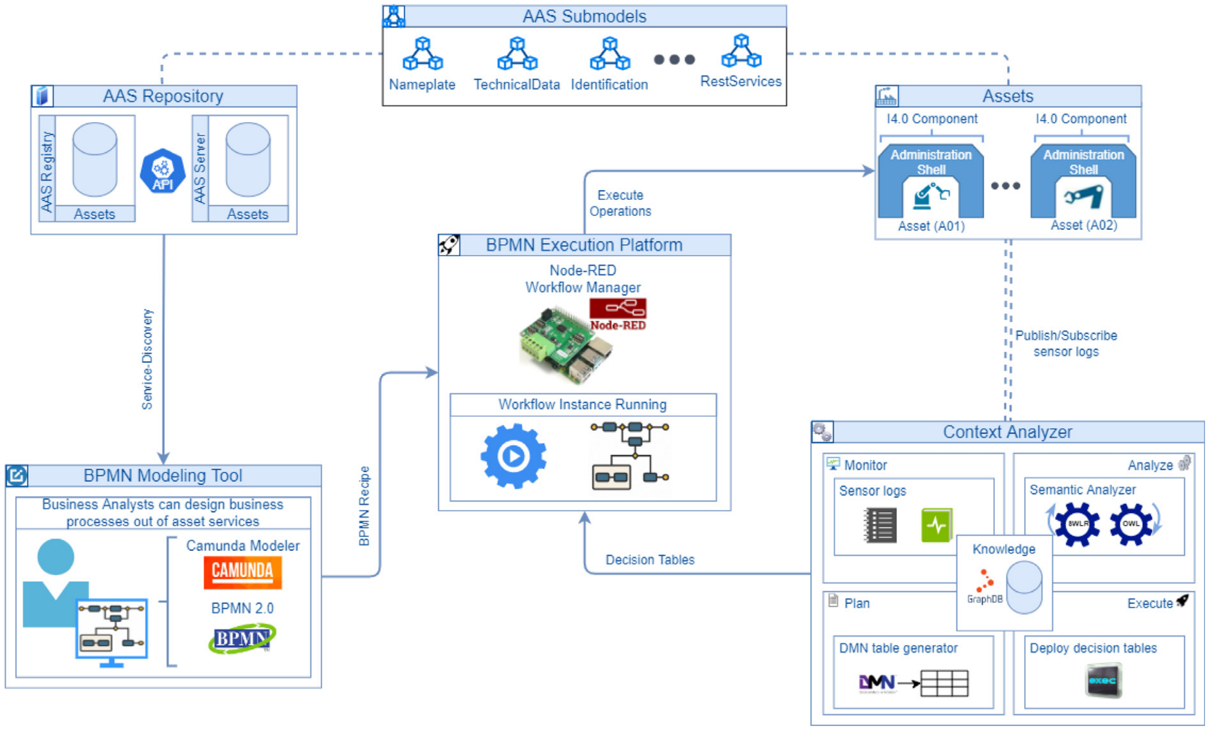

Fig. 10. Architecture for context-aware workflow management: An asset administration shell-based approach.

a proposal is presented to address the identified gaps in the state-of-the-art.

6. Architecture for context-aware workflow management: An asset administration shell-based approach

In this section, we propose an architecture to address the challenges identified in Section 5. The proposed architecture orchestrates AAS-based business processes and provides context-awareness capabilities to enhance the decision-making dimension of business processes at runtime. The basic details of the proposal are outlined in the present paper, further details can be found in the expanded description in [98].

The architecture, as shown in Fig. 10, comprises several components:

1. "Assets" (top-right) represent I4.0 physical devices at plant level. These assets are digitized through the AAS concept and their digital representations are stored in a repository.
2. "AAS Repository" (top-left) can be an AAS Server or an AAS Registry, depending on the vendor implementation (e.g. Basyx, NOVAAS, Admin-shell-io, etc.).
3. "RestServices" submodel (top-middle) is proposed to allow the description of machine services.
4. "BPMN Modeling Tool" (bottom-left) includes the Camunda Modeler and a novel Camunda plugin, "AAS Web Service Discoverer", that discovers services from assets in the AAS Repository.
5. "BPMN Execution Platform" (center) manages the orchestration of asset services, using any workflow executor or business process executor that can interpret and run recipes written in BPMN.
6. "Context-Analyzer" (bottom-right) monitors and plans adaptations in response to context changes, to enhance the dynamicity of workflows at runtime. This component is based on IBM's MAPE-K framework for building autonomous systems.

This proposal provides a comprehensive solution that combines the use of semantic web, business processes, and the AAS industry standard in an edge computing environment. To the best of our knowledge, no approach exists that performs dynamic re-selection of services using these three elements together. While there are similar approaches that incorporate semantic web for context recognition and service re-selection, these are typically cloud-based and do not utilize the AAS standard for asset representation. The developed components of this architecture are open-source, licensed under the Apache-2.0 license for community use and further development.[5]

7. Conclusions

The business process management discipline is gaining traction in the smart manufacturing domain as it facilitates the design of formal standardized workflow recipes. This technique, combined with semantic web technologies, delivers context-aware systems which can enhance the decision-making process in response to context changes.

In this work, state-of-the-art of semantic web-enhanced workflow management approaches in the smart manufacturing domain were reviewed systematically by applying the PICOC method. Thirty-six studies published between 2015 and 2022 were selected and analyzed. The wide range of topics covered in the study presented certain challenges, as it made it difficult to classify the selected works. Nonetheless, the review can be considered successful in identifying challenges in the field and addressing the research questions (Section 5.1).

Our analysis highlights opportunities for future development in technical aspects such as considering semantics for context awareness and standardizing process modeling, as well as architectural concerns including security and scalability. Trending tools and algorithms used for building semantic and context-aware smart manufacturing solutions are also identified. Additionally, the review examines the factors and datasets commonly used for evaluating such approaches, yielding information for

5 https://github.com/MUFacultyOfEngineering

building solutions with the right tools, practices, and standards. Finally, a novel architecture is proposed in Section 6 that addresses the challenges identified in the literature and utilizes the best practices and standards uncovered in the study.

This research provides a valuable resource for both novices and specialists in the field and lays the foundation for future research efforts. In particular, our innovative context-aware workflow management architecture can be enhanced by addressing the challenges identified in the present literature review: (1) a need for standardization in process modeling and service-oriented architecture solutions, (2) a need to assist process designers in the modeling of manufacturing business processes, (3) a need for business process management software that can take advantage of the edge computing environment, and (4) a need to interpret contextual information to perform dynamic adaptations. We plan to address these needs by developing the necessary components and providing a standardized solution for industries seeking to adopt the AAS standard in their manufacturing processes.

CRediT authorship contribution statement

William Ochoa: Conceptualization, Methodology, Software, Writing – original draft. **Felix Larrinaga:** Supervision, Validation. **Alain Pérez:** Software, Supervision, Validation.

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

No data was used for the research described in the article.

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