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RESEARCH ARTICLE

Semantic Modeling, Development and Evaluation for the Resistance Spot Welding Industry

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ABSTRACT The ongoing industrial revolution termed Industry 4.0 (I4.0) has borne witness to a series of profound changes towards increasing smart automation, particularly in the industrial sectors of automotive, aerospace, manufacturing, etc. Automatic welding, a widely applied manufacturing process in these domains, is not an exception to these changes. One type of automatic welding, Resistance Spot Welding (RSW), lies at the center of this work. Large volumes and varieties of RSW data are being generated, thanks to the technologies behind I4.0. To address the associated data challenges, ontologies are essential in various aspects: integrating data sources, enhancing interoperability, and unifying knowledge etc. However, there have been limited studies around the semantic modelling of Resistance Spot Welding: Existing ontologies have overlooked some crucial concepts, such as an operation-centric view, welding software, and welding electrodes, which are essential for the monitoring of sensor measurements as well as the status of machine components (e.g., electrode wear). Additionally, current ontologies are not publicly available (to the best of our knowledge), and therefore cannot be accessed by other users. Such a lack of availability often requires that users build their ontologies from scratch. In this paper, we propose our RSW ontology (RSWO) (RSWO is publicly available at https://w3id.org/def/mo-rswo) to formalize knowledge in the RSW domain. It combines three sources of knowledge: extensive discussions with Bosch welding experts; reusing terminologies following ISO-14327 and ISO-14373 standards; and existing established ontologies. We have evaluated RSWO on real-world data from monitoring welding quality at Bosch in Germany, using Competency Questions, FAIR principles, OOPS!, and OntoMetrics.

INDEX TERMS Resistance spot welding, semantic modeling, ontology, smart manufacturing, knowledge representation.

I. INTRODUCTION

Industry 4.0 refers to a series of profound changes towards a high degree of inter-connectivity and smart manufacturing, involving large volumes and a variety of data in various industries [1], such as automotive, aerospace, manufacturing, etc. Resistance Spot Welding (RSW) is an automated manufacturing process widely applied for joining metal materials in these industries [2]. Worldwide RSW accounts for the production of over a million cars every year [3]. In the RSW process, a high current flows through metal worksheets, generating a large amount of heat and melting down the metal materials to form welding spots. This is a highly complex process where mechanical, chemical, and electro-magnetical effects are intertwined. The welding robots are equipped with many sensors that measure in a millisecond base, generating a substantial amount of data. With the increasing dynamicity of customer individualization and the demanding variety of resource-production settings brought by global lean manufacturing, the requirements for handling the large volume

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and variety of RSW data are rising significantly. Ontology is a proven technology for handling such data issues.[1] It typically addresses the issue of different and unstructured formats that are not directly interoperable but requires high efforts to be prepared to a unified format for subsequent data analytics to create added value. Ontology provides a shared conceptualization to capture the knowledge and meaning [6], which are essential as a common base between the information requester and provider [7] for domain understanding, data understanding, data integration, and further analytics applications such as data inspection, information summary, diagnostics. It has been widely applied in various industrial areas, such as steel-making process [8], robot collaboration [9], 4D printing [10], additive manufacturing [11], etc.

However, when industrial users attempt to rely on the powerful tool of ontology for addressing real-world data issues, it turns out the existing ontologies fall short of addressing issues crucial for industrial usage: (1) the current RSW ontological models are tailored to specific scenarios and overlooked crucial concepts of the welding domain such as electrode wear count, electrode dress count etc. (Details see Table 1) [12], [13], [14], [15], [16]. These concepts are essential for capturing knowledge that is used in a quality monitoring (e.g., *find the Q-Value concerning power and voltage measurements in an operation*?) and diagnostics (e.g., machine component status, *Is there any wear count on the particular electrode*?), etc. (2) the reusing of the existing ontologies was understudied, which is one of the linked open data principles. (3) existing welding ontologies insufficiently studied systematic assessment for knowledge capture, quality, and richness. (4) the existing ontologies built so far (to our best knowledge) are not publicly accessible to the users for reusing purposes.

To address the above issues, this paper presents an RSW ontology (RSWO) that is developed based on and assessed on the industrial scenario at Bosch. RSWO combines knowledge from three sources: knowledge acquired from experts working with Bosch; the concepts are aligned with ISO-14327 and ISO-14373[2] that is under practice in Bosch welding production and existing ontologies. The RSWO is assessed in compliance with the FAIR guiding principles using O'FAIRe methodology [17]. The RSWO structural and functional, and quality and richness dimensions are assessed using OOPS and OntoMetrics, respectively. Furthermore, to follow best practices regarding linked open data; it is made sure to reuse the ontology terms from existing relevant ontologies. The final version of the developed ontology is made publicly available for users.

This makes a good balance between the standard knowledge and first-hand experience from welding experts working with Bosch. Moreover, RSWO is extensively assessed on industrial datasets against knowledge capture after meticulous negotiation and examination, we can make the ontology publicly available, so that academic and industrial users can access the ontology for reuse purposes.

The contribution of this paper is summarized below:

(1) We propose a Resistance Spot Welding Ontology (RSWO) that formally describes the Resistance spot welding operation, machine and machine parts, and software systems. It models the RSW domain knowledge, harmonized with the standard ISO-14327 and ISO-14373, and reuses existing ontologies (e.g., RGOM). The three sources ensure rigorous terminology and incorporation of first-hand knowledge. RSWO provides a broader coverage of concepts of RSW welding, compared to the existing ontologies which focused on specific applications.

(2) A summarizing comparison of existing RSW ontologies and RSWO, on the concepts coverage. It enabled us to introduce the concepts that are missing and aligned them with the terminology used in standards and experts.

(3) A systematic ontology development process is demonstrated in a real industrial case, with experts and data in a world-leading industrial partner. The development process includes domain analysis for knowledge acquisition and formalization of the concepts with implementation and validation. This can serve as an example of ontology engineering in the industry.

(4) Besides, in comparison to the existing RSW ontologies that focus on concept modelling, our ontology is utilized and implemented with real data from Bosch welding production. Furthermore, we evaluated RSWO with O'FAIRe methodology for FAIR principles, using OOPs! tool to assess the structural and functional dimensions quality to assess the clarity, completeness, consistency and conciseness of the proposed ontology, and the OntoMetrics tool to measure ontology attributes richness of the RSWO containing data instances.

The rest of the paper is organized such that Section II reviews the state-of-the-art related work. Section III explains the ontology development process. The reuse of contemporary ontologies is presented in Section IV. Section V elaborates on the RSW Ontology. The developed ontology

[1] We briefly introduce ontology here and refer the readers to [4] and [5]. In essence, an ontology is a formal specification of a domain of interest to describe a set of concepts (e.g., `WeldingMachine`, `WeldingElectrode`) and the relations between these concepts (e.g., etc). It is written in a set of first-order logic formulae of a special form over atomic classes (concepts) and properties (relations), where each formula essentially says that one atomic class (resp. property) is a subclass (resp. sub-property) of another, and complex classes (resp. properties) are composed of the atomic classes and properties (resp. properties) using logical *and*, *or*, *not* as well as universal and existential quantifiers. Reasoning over ontologies allows us to compute logical entailment.

[2] We are aware that there are other relevant standards (e.g., BS 1140, AWS C1.1M/C1.1:2000, etc., but the welding standards are subject to inconsistency/contradictions of terminologies/definitions between the standards [12]. Besides, after discussion with Bosch experts, we consider ISO-14327 and ISO-14373 standards sufficiently comprehensive for the ontology discussion in this work. To make the terminology consistent, we choose ISO-14327 and ISO-14373 in our practice and leave the unification of the terminologies between other standards as future work. Moreover, the alignment with top level ontologies will be also included in future work.

is assessed in Section VI. Conclusion and Future directions are in Section VII.

II. RELATED WORK

Over the years, ontologies have played an important role in information modelling and knowledge management. It provides a formal description of concepts and relations that enables the stakeholders to share and reuse the knowledge with each other. This section presents a comprehensive overview of the ontologies proposed and developed for smart manufacturing. Then, the ontologies specifically developed for resistance spot welding are focused.

A. ONTOLOGIES FOR SMART MANUFACTURING

The subsection provides an overview of the ontologies developed to address the challenges in the smart manufacturing process, resources, and products. In the past two decades, the Semantic Web, Linked Open Data (LoD) and Ontologies have emerged as significant tools to support data modelling, collaboration, adaptation and interoperability [18]. Ontologies have been widely used to model the concept of a device and the process it performs in preparing for embracing the needs of smart manufacturing, where humans and robots will be in direct interaction and performing collaborative work tasks. The knowledge representation via ontology has supported solving problems such as interoperability between standards and hardware and IoT devices in modelling related-domain knowledge. In the most recently reported work, the authors have suggested Semantic Integration at Bosch (SIB) framework for surface mounting process pipeline analysis by integrating Bosch production data [19]. To experiment with their architecture, they used surface mounting (SMT) to map data from the manufacturing line. Relevant reported work has combined domain ontologies on top of SMT ontology to address in the production line data the problem of interoperability, a crucial factor for enabling efficient integration and access of manufacturing data for realising the applications of Industry 4.0 [20]. In [21], the authors have developed an ontology to represent the industrial production process from order to completion by combining the base, product, process, device, and parameter ontologies. The ontology is built on top of the product, process, device, and parameter ontologies to provide interaction with each other. Furthermore, the order term is represented as a distinct ontology that is associated with the term product. The service-oriented architecture is built on top of this ontology model to dynamically discover, select, organize, and consume semantic web services [22]. The authors in [23] have used the manufacturing resource, process, and product terms from the ISA-95 standard and semantic web rule Language (SWRL) to infer implicit in- formation, allowing them to check the machinery required to generate product variations to design flexible and information-rich production models. Saeidlou, S. et al. have designed an ontology model for the manufacturing domain and developed a semantic query algorithm to investigate the semantic richness of an intelligent data query system in the proposed ontology model [24]. Wan et al. have proposed an ontology for resource configuration that has utilized web ontology language (OWL) to represent the domain knowledge of the reconfiguration of sensible manufacturing resources [25]. Their goal had been to use an ontology-based resource integration architecture to integrate the cyber-physical systems (CPS) equipment. The produced data is saved in a relational database for being connected with and mapped into the individuals of the manufacturing ontology model. An intelligent manipulator has been used as a test case for the suggested resource reconfiguration ontology as a proven manufacturing practicality.

B. ONTOLOGIES FOR RESISTANCE SPOT WELDING

Besides representing the manufacturing production line domain knowledge, ontologies have also been proposed to formalize the welding domain. Table 1 compare the existing welding ontologies with RSWO. Some of the crucial concepts of the welding operation, welding machine and electrode which contribute to useful knowledge of RSW are listed in the table. The green colour check marks show the concepts used by each ontology. On the other hand the overlooked concepts are cross marked with red color.

In a recent work by [26], the authors proposed an ontology that is based on the definitions of foundational concepts to characterize the joining operations. In another work, the authors in [12], proposed Core Domain Ontology for Joining Processes (CDJOP) to semantically categorise the joining processes to address the issue of semantic inconsistency in standardization documents. Their work lacks to provide any information about any input from the domain experts regarding the semantic inconsistency being targeted. They could not illustrate the utilization of ontology in a real industry scenario nor its implementation is demonstrated with industry-based data. Furthermore, they omit to mention or highlight the core concepts such as squeeze time, hold time, spatter and its occurrence time, Wear and dress count etc. In another work [13] the authors have used an automotive OEM dataset to extract decision rules by using Classification and Regression Trees (CART). The extracted decision rules are systematically transformed into SWRL rules to capture the semantics and improve the shareability of the so-created knowledge domain. Their work has entirely relied on the rules that were extracted from the data, which is the main drawback of their ontology. Their model is based on the rules derived from data which is hard to interpret in terms of semantics.

The authors in [14] have formalized the domain knowledge related to the welding process by proposing ontological modelling for the welding process. The knowledge and information associated with the welding process are only limited to a few categories of welding. The ontology is unable to represent the knowledge about how a welding procedure is performed, and what machine settings have been adopted for serving what kind of parameters. Alongside this, most of the proposed work has focused on enriching machine-learning models to

TABLE 1. A comparison of the domain knowledge coverage provided by the proposed RSWO and the current resistance spot welding ontologies.

Ontologies	Welding Operation					Welding Machine				Electrode				Others	
	Weld	Squeeze Hold	Spatter	Spatter Occurence Time	Parameters Reference Value	WeldingGun	WeldingRobot	Electrode	Software ControlSystem	ElectrodeClass	DressCount WearCount	NoseType	Electrode WorkPiece Interaction	Measureing Unit	Available Online
[13]	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✓	✗
[26]	✓	✓	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
[12]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗
[14]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗
[27]	✓	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓
[15]	✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓	✗
[16]	✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✓	✗
RSWO	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

predict welding quality [15], [16], [28]. Their machine learning models are based on ontologies to annotate data and its features to improve the training of machine learning models. Dong et al. scrapped and parsed online unstructured data and transformed it into machine-interpretable data through their developed WeldGalaxy Ontology [27]. They have made their ontology file available online and can be accessed. The WeldGalaxy ontology, however, exclusively focuses on arc welding, and the method utilized to construct the ontology is unclear. Moreover, their ontology contains insufficient object properties as compared to their defined classes which left the classes unconnected.

C. OPEN CHALLENGES

This literature review reveals two main challenges in connection with ontologies for RSW. First, most of the current ontologies overlooked some of the domain knowledge of the RSW. This is likely due to that these ontologies are tailored to specific applications and focus on particular tasks such as solving the issue of semantic inconsistencies in the welding standard documents, weldability prediction with semantic rules, and enhancing machine learning models to predict weld quality. These ontologies overlooked important concepts and relationships e.g., machine software for monitoring and measuring the critical-to-process parameters of a resistance welding operation. In addition to the above, these ontologies are not publicly available. It consumes a lot of time and effort to build an ontology from scratch. Additionally, the ontology development process with a real industrial case is insufficiently covered by the literature: we need more examples that demonstrate the development and values of ontologies in the industry. To address these issues, this paper aims to develop RSWO that can be used as a reference ontology by different users in the industry. The ontology is made available online to be reused by others which reduces the effort required in designing a similar ontology for RSW.

III. ONTOLOGY DEVELOPMENT PROCESS

There exists a number of methodologies for ontology development in the literature. These methodologies provide a step by step guidelines for designing and developing ontology engineering including the construction of classes, and relationships. Some of the most popular ontology development methodologies are Enterprise Model Approach [29], METHONTOLOGY [30], Common-KADS [31], and Linked Open Terms (LOT) [32]. In this work, we take on the LOT methodology [32] that is a refined work of based on the top for developing RSWO. The reason we select this methodology is that it provides a gradual refinement process throughout the ontology creation. This refinement ensures the ontology captures the domain knowledge concepts as well as the low-level manufacturing data. The ontology development process is shown in Figure 1.

A. ONTOLOGY REQUIREMENT SPECIFICATION

We have used a number of sub-activities from the ontology requirement specification. With the help of Bosch experts, it is identified why there is a need for an RSW ontology. This is specified with the use-case (Quality Monitoring in Resistance Spot Welding). In relation to this, several documents were provided including ISO standards, datasets description, and datasets itself. The aforementioned activity thus helped in the identification of the purpose and scope of the RSW ontology (unified model for questioning answering related to RSW). Considering the scope of the RSW ontology, the functional requirements are collected in natural language sentences (e.g., *Resistance spot welding operation consume power*) from the Bosch experts as the experts have zero knowledge about ontology that must be answered by the ontology. The natural language sentences are then transformed into competency questions. Some of the Competency questions are listed in Table 2. These CQs are provided by the welding experts. They are grouped into 2 categories:

(1) Data Inspection: (CQ1-CQ5) We used RSWO-based Bosch welding process data to examine it from a variety of angles including the one listed in Table 2. We inspected the data during, and after the welding operations for the objectives of verification and quantification of welding quality.

(2) Diagnostics: (CQ6-CQ10) We performed different diagnostic tasks such as dressing required, spot repetition occurred, the occurrence of any spatters, and others listed in Table 2. Besides, the diagnostics enable the user to learn more about the surrounding

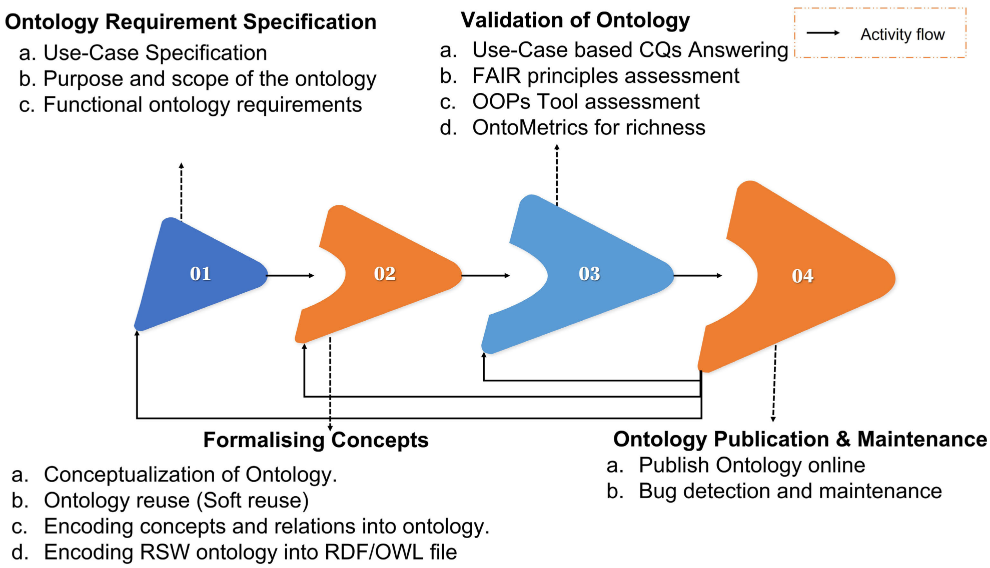


FIGURE 1. Steps used in the ontology development process.

irregularities to comprehend what occurred nearby and identify potential root causes.

Finally, when these functional requirements are successfully approved we moved on to the second activity of the ontology development.

B. FORMALIZING CONCEPTS

We have divided the LOT second activity (Ontology implementation) into Formalizing Concepts and Validation of ontology for the successful construction of the ontology. The Formalizing Concepts activity contains the first three sub-activities i.e., ontology conceptualization, ontology reuse and ontology encoding. In order to conceptualize the knowledge of RSW, the terminology i.e., classes and relations are first searched in the existing ontologies. The terminology found is reused in the RSWO otherwise new concepts are introduced and created if not found. The formalisation process of concepts with relationships is as shown in Figure 2. For example, a concept named `WeldingMachine` has been created to model a welding machine with a property such as *hosts* that defines the relationship between WeldingMachine and the Part. The `WeldingMachine` is further linked via the *performsA* property with the `AssemblyProcess` concept, and it is then linked to the *hasOperations* relationship with the concept *RSWOperation*. RSWOperation is shown to be linked with the concept Assembly through *hasRawProduct* property. The *isOperationProductOf* property is used to connect the concepts `WeldSpot` and `RSWOperation`.

Upon formalizing the concepts, it is implemented using the open-source ontology editor of Protege[3] for developing intelligent systems. The RSWO is encoded into Resource Description Framework/Web Ontology Language (RDF/OWL).

[3]http://protege.stanford.edu/

Furthermore, general ontology such as Time ontology [33], Sensor ontology [34] concepts have also been reused to add context to the data that add more knowledge, for instance, the temperature observation of the machine during a process at a particular time, timestamp, can be added to the machine concept as its property. Object properties such as *isPartOf* and *hasPart* from the Dublin core ontology have also been reused in order to follow the best practices of Linking Open Data (LOD).

C. VALIDATION

Now we discuss the validation step of the ontology development process that is utilized to assess the RSWO through several metrics: Use-case based Competency Questions (CQs) answering, Findable, Accessible, Interoperable, Reusable (FAIR) principles, Ontology Pitfall Scanner! (OOPS) and OntoMetrics. The Use-case based CQs answering is performed on the Bosch Production data to demonstrate the functionality and utilization of RSWO. The CQs were provided by the Bosch experts. The CQs determined whether the RSWO ontology has captured the domain knowledge; for example the diameter of the weld spot produced in a certain welding operation, the weld force applied to workpieces, and the resistance between electrode and workpiece.

Moreover, the O'FAIRe methodology assesses the FAIR principles, and the OOPS tool evaluates the structural, and functional dimensions of any ontology to analyze its clarity, completeness, conciseness and consistency. It is widely used among researchers to identify flaws and pitfalls in ontology design [35]. The missing domain and range in the properties, creating unconnected elements in the ontologies are some of the pitfall examples that are checked by the OOPS. Also, the ontology populated with data instances is uploaded to

TABLE 2. Competency questions provided by Bosch experts.

Data Inspection	CQ1	How much weld force, voltage, current and power is utilized in an operation?
	CQ2	What machine parts are being used in a resistance spot welding operation?
	CQ3	How much force is utilized in the squeeze, weld and hold step of the operation?
	CQ4	How much is the resistance between the bottom Electrode and bottom sheets?
	CQ5	How many cycles of weld time is utilized in an operation?
Diagnostics	CQ6	Find all those values of Q-Value higher than a threshold along with their voltage and power in an operation.
	CQ7	Is there any spatter that occurred during a particular time?
	CQ8	Does the electrode require dressing?
	CQ9	How many weld spots have spot repetition?
	CQ10	How much force is utilized in the squeeze, weld and hold steps of the operation?

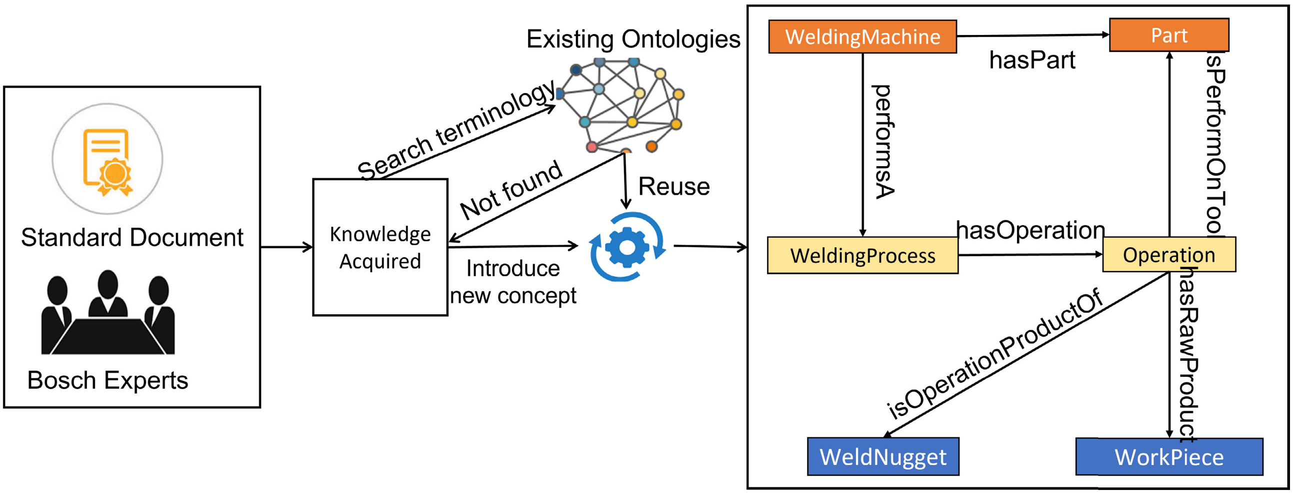


FIGURE 2. Semantic illustration of our process for knowledge formalization. The middle of the figure shows the procedure of terminology selection, and the right side shows the formalized knowledge. On the right side of the figure, the concepts in orange color show the terms related to manufacturing resources while the concepts in yellow provide the terms process (RSWProcess) and operation (RSWOperation), and the blue color provides the terms workpiece and weld spot, respectively.

OntoMetrics[4] for advanced analytics. The details of the RSW validation are explained in the assessment section.

D. ONTOLOGY PUBLICATION AND MAINTENANCE

We made the RSWO available online at GitHub which is accessible. The metadata is published on the industry portal and contains information such as URI, license and title used. It also contains information such as creator, contributor, endorser, date of creation and others. Additionally, to maintain the ontology, the bugs can be reported on the GitHub page that can be tracked.

IV. REUSE OF CONTEMPORARY ONTOLOGIES

In this work, we have aligned the RSWO by reusing relevant existing ontology and vocabulary. Reusing existing vocabulary from contemporary ontologies is important to enhance interoperability and to facilitate knowledge reuse [36]. The existing ontologies are analysed based on the context of their ontological terms of classes and relations between them in the first step of the ontology development methodology. For this purpose, relevant terms are identified based on their semantic context with the RSW domain of the Industry Ontology Foundry (IOF) repository[5] that includes 52 ontologies representing the manufacturing industry. The IOF is a group that is developing a set of open reference ontologies to support the demands of the engineering and manufacturing sectors, and accordingly to enhance data interoperability. Table 3 shows the prefixes and Internationalised Resource Identifiers (IRI's) used in the RSWO. and Table 4 shows some of the object properties being reused from the existing ontologies.

TABLE 3. Prefixes and IRIs used in the RSWO ontology.

Prefixes	Namespaces
rswo:	http://www.rswo.org/2022/7/rswo#
sosa:	http://www.w3.org/ns/sosa/
swo:	http://www.ebi.ac.uk/swo/
time:	http://www.w3.org/2006/time#
dc:	http://purl.org/dc/terms/
uom:	http://purl.obolibrary.org/obo/
owl:	http://www.w3.org/2002/07/owl#
rdf:	http://www.w3.org/1999/02/22rdfsyntaxns#
rdfs:	http://www.w3.org/2000/01/rdfschema#
xml:	http://www.w3.org/XML/1998/namespace/

Table 5 shows the concepts and their definitions used in the RSWO. The Source column in Table 5 shows the origin

[4] https://ontometrics.informatik.uni-rostock.de/ontologymetrics/

[5] http://industryportal.enit.fr/ontologies

TABLE 4. Some of the properties reused from the existing ontology.

Reused property	Ontology
sosa:hosts	Sensor Ontology
sosa:hasProperty	Sensor Ontology
sosa:observes	Sensor Ontology
time:hasTime	Time Ontology
dc:hasPart	Dublin core Ontology
dc:isPartOf	Dublin core Ontology
om:hasUnit	Unit of measure ontology
rgom:performsA	rgom ontology
rgom:hasOperation	rgom ontology

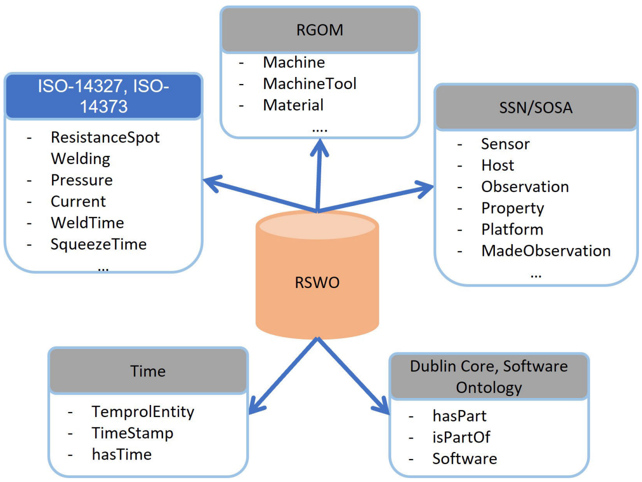


FIGURE 3. Ontology terms acquired from existing ontologies (highlighted in grey color) and, ISO standards (highlighted in blue color). The number shows the statics of the classes being used from; 74% Domain experts and ISO standards, 11% RGOM, 6% Sensor ontology, 7% uom and 2% others.

TABLE 5. Examples of the classes, their definitions and knowledge source; DE: domain experts.

Ontological term	Definition	Source
RSWOperation	A resistance spot welding operation contains a set of activities such as squeeze, weld, and hold the worksheets to a weld spot.	DE
WorkPiece	A workpiece is an item that is being processed into another desirable shape. Typically, the workpiece is a chunk of reasonably stiff material like stone, wood, metal, or plastic.	DE
PiecePiece interaction	The class PiecePieceInteraction is used to model interaction properties between physical entities. For example, between the two worksheets of RSW, there could exist adhesive; between any two contacting physical entities, the contact properties like thermal or electric conductivity.	DE
WeldProgram	The weld program is the already planned parameter's reference value or setpoints for an operation.	DE
Weld Spot	A weld spot is the output of an operation and it is a join that has been spot-welded. It is the product of the RSW operation.	DE, ISO-14327, ISO-14373
Wear	Electrode wear can occur due to heavy splash, mushrooming or alloying. This can have an adverse effect on the reproducibility and validity of the results.	DE, ISO-14327, ISO-14373
Software	Computer software, or generally just software, is any set of machine-readable instructions (most often in the form of a computer program) that conform to a given syntax (sometimes referred to as a language) that is interpretable by a given processor and that directs a computer's processor to perform specific operations.	The Software Ontology
Observation	An Act of carrying out an (Observation) Procedure to estimate or calculate a value of a property of a FeatureOfInterest.	SOSA Ontology
Unit	A unit of measure is a definite magnitude of a quantity, defined and adopted by convention or by law. It is used as a standard for measurement of the same quantity, where any other value of the quantity can be expressed as a simple multiple of the unit.	units of Measure Ontology
TemporalEntity	A temporal interval or instant.	Time ontology

from where the concepts are derived. It can be observed that the concepts have been reused from what is called Sensor, Observation, Sample, Actuator (SOSA) ontology that provides formal light-weight general-purpose specifications of concepts as entities in the modelling. Also, it shows the interaction between the entities involved in the acts of sensing, actuation, and sampling, time ontology, and ontology of units of measurement (uom). Figure 3 shows an overview of terms being reused from relevant existing ontologies along with those from ISO-14327 and ISO-14373.

A. ALIGNMENT WITH THE DOMAIN LEVEL ONTOLOGY

We have considered aligning the RSWO with domain-level ontology. The domain-level ontology is very important and provides semantic interoperability across the domain. There exists several domain level ontologies such as MASON [37], CDM-Core [38], RGOM [39] etc. We have selected RGOM as it is built on reusing the manufacturing ontologies with the terms being introduced that are overlooked in the previously existing vocabularies. In order to illustrate the alignment with the domain level ontology (RGOM), consider Figure 4. The figure shows the alignment of RSWO (orange color) to the RGOM ontology (green color). For example, the class `RSWMachine` of RSWO is created as a subClass of `Machine` and the `Electrode` class in the RSWO is created as a subClass of `MachinePart` of RGOM. The `RSWMachine` class is linked to the `Electrode` class through the property *hasPartElectrode* which is the subProperty of *hasPart* of the RGOM (hasPart properties is reused from the Dublin core vocabulary by RGOM). In future work, the RSWO will be aligned to the top-level ontology.

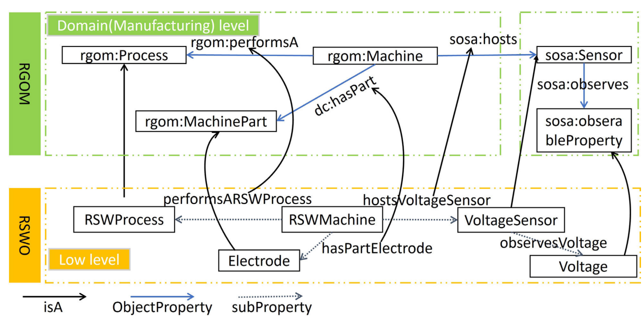


FIGURE 4. Alignment of the RSWO ontology with the domain level ontology.

V. RESISTANCE SPOT WELDING ONTOLOGY

The RSWO ontology description is provided here which has been implemented in OWL in the light of the methodology described in Section III. The primary purpose of using OWL is to provide a widely accepted information-sharing environment in order to improve RSW processes. The classes, object and data properties used to construct the RSWO is shown in Figure 5, 6 and 7 respectively. Furthermore, we exemplified our ontology with simplified Semantic Web Rule Language's (SWRL) syntax in the following subsections. The developed RSWO ontology is comprised of the metrics listed in Table 6. Moreover, there are a total number of 112 classes, 98 object properties and 71 data properties in the RSWO.

TABLE 6. Ontology metrics.

Metric	RSWO
Axioms	1164
Logical axioms count	469
Declaration axioms count	287
Class count	112
Object property count	98
Data property count	71
Individual count	0

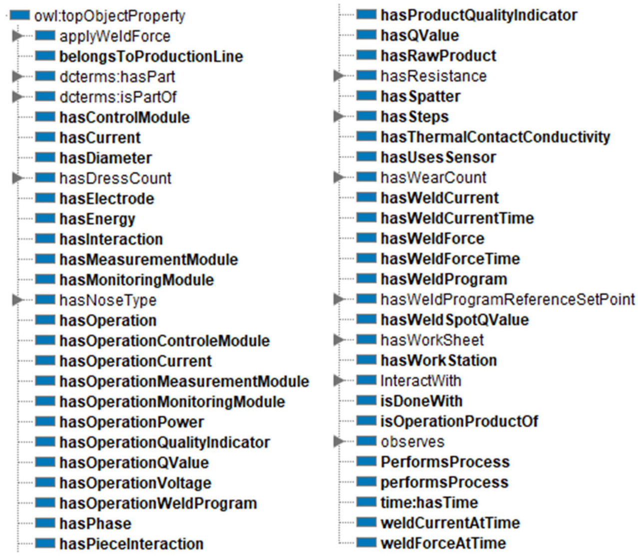


FIGURE 6. Object properties and data properties of RSWO.

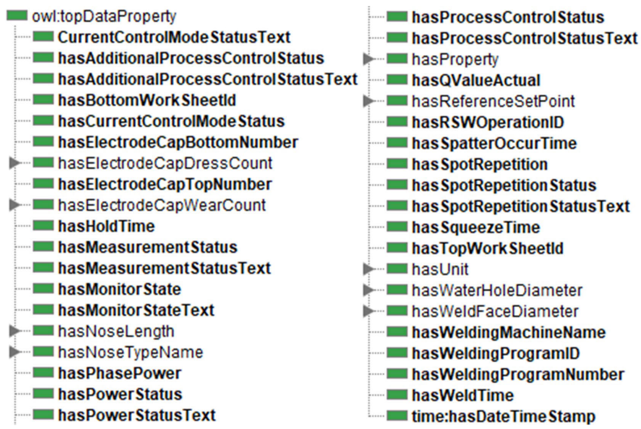


FIGURE 7. The data properties of RSWO.

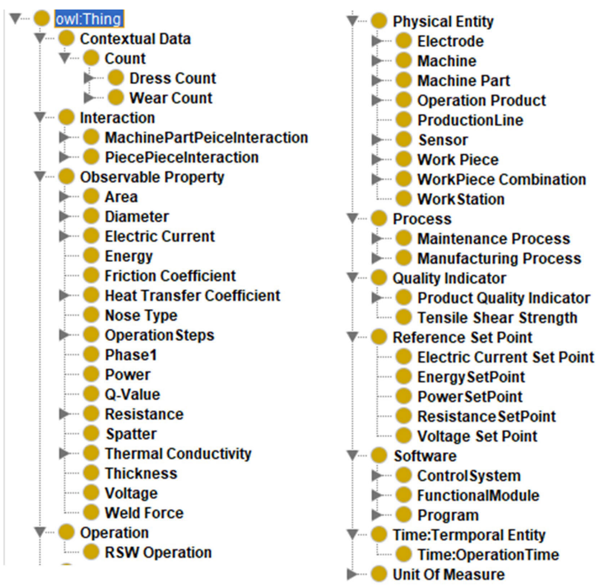


FIGURE 5. Class hierarchy of RSWO.

A. OVERVIEW OF RSW PROCESS AND THE ONTOLOGY

Resistance Spot Welding (RSW) is frequently used in the automotive sector, for example, in the manufacture of vehicle bodies. This process is controlled by welding control systems that store weld configurations. In the resistance spot welding process, the welding gun is equipped with electrodes that end with caps to press two or three worksheets. Then, an electric current flows from one electrode, through the worksheets, to the other electrode, generating a large amount of heat due to electrical resistance. The material in a small area between the two worksheets, called the welding spot, will melt, forming a solder mass that connects the worksheets.

In connection with the above description, the ontology of resistance spot welding has been developed that provides the automotive welding industries with a common knowledge architecture. Figure 8 depicts the main classes and characteristics of the RSW ontology. The ontology has reused the domain core concepts such as `Machine` and `Operation` to facilitate inter-domain data integration. The subclass of the `Machine` is the `WeldingMachine` that contains a number of machine parts. The figure represents the parts of the machine with the class `MachinePart`, which is linked to the class `Machine` via the object property *dc:hasPart*. On the other hand, RSWOperation is a subclass of the domain core concept Operation. Axioms 1 and 2 define the subclass constraints in the RSWO and axiom 3 shows the constraints that every WeldingMachine performsA some RSWOperation in Description logics (DL).

axiom 1: $WeldingMachine \sqsubseteq RGOM : Machine$

axiom 2: $RSWOperation \sqsubseteq RGOM : Operation$

axiom 3: $RSWOperation \sqsubseteq \exists performsA^{-}.Welding$ $Machine$

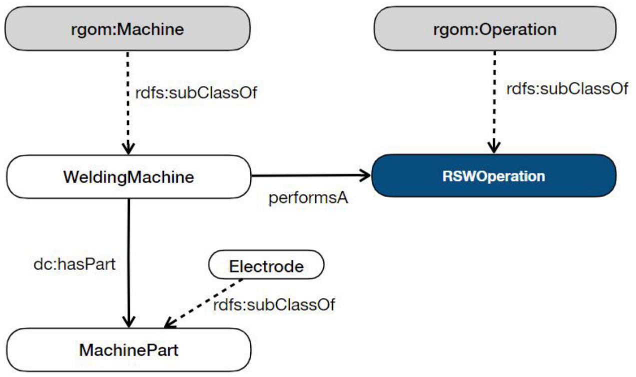


FIGURE 8. **Overview of core concepts in the RSW ontology.**

In the following subsections, we will go to the detailed modelling of these concepts.

B. RESISTANCE SPOT WELDING OPERATION

Resistance Spot Welding (RSW) is a complex task that is widely used in diverse applications such as vehicle body parts, railway tracks, turbine blades, etc. [40]. It contains a number of activities that are performed to produce welding processes. An operation is an atomic process that takes in the worksheets as raw products in order to produce a product output, namely a welding spot.

RSW Operation modelling is as shown in Figure 9 that shows that class `RSWOperation` is linked to the `WorkPieceCombination` class through *hasRawProduct* object property. In the RSW operation, an assembly is the raw product which is the subclass of the `WorkPieceCombination`. The class `Assembly` has parts such as `TopWorkSheet` and `BottomWorkSheet` that are the subclasses of the `WorkPiece`. The property *dc:isPartOf* connects *WorkPiece* with *Assembly*.

Furthermore, RSW operation has an electrode that applies pressure to the aligned workpiece point of interest. It can be observed from the top of the figure that `RSWOperation` and `Electrode` classes are related via *hasElectrode* property. In addition to this, the `WeldForce` class is linked through the *applyWeldForce* relation to `Electrode`. After applying the pressure, a constant current is applied through the electrodes into the *WorkPieces*. Based on this description, the right side of the figure illustrates the welding conditions maintained during the RSW operation are that the `WeldCurrent` and `WeldTime` has a constant `WeldForce` or the `WeldCurrent` and `WeldForce` in the welding has a constant `WeldTime`. This bring out an internal resistance in the worksheets and in results produces a weld spot as a product. The `WeldSpot` and `RSWOperation` classes are linked through *isOperationProduct* relation (left side of figure). The RSW operation has the date time on which the operation is executed, so the *hasTime* property from the time vocabulary is reused to link the operation class to its date time data instance.

We exemplify the operation part of the ontology with an example about the weldspot (left side of 9) using DL. The weldspot diameter is also an operation quality indicator. Axiom 4 represents the axiom that for every `RSWOperation` there exists some `WeldSpot` and `WeldSpot` is the (operation) product of `RSWOperation`. Axiom 5 specifies that a `WeldSpot` has some value `Q-Value`.[6] Axiom 6 also specifies quality indicator (`Diameter`) that a `WeldSpot` has exactly one diameter.

axiom 4: $RSWOperation \sqsubseteq \exists isOperationProductOf^{-}.WeldSpot$

axiom 5: $WeldSpot \sqsubseteq \exists hasQValue.QValue$

axiom 6: $WeldSpot \sqsubseteq = 1 hasDiameter.Diameter$

C. WELDING MACHINE AND SOFTWARE

We now shortly introduce the welding machine and its software. A RSWOperation is performed by a welding machine. The welding machine consists of several parts such as a welding robot, welding gun, electrode, sensors etc. that carry the commands of the software systems to carry out the required operation. The welding machine is controlled by a software system to perform the desired designed welding operation. The software system known as the RSW control system has three modules, each of which has a specific task, that is, the monitoring module monitors the quality of the weldspot and operation, the control module provides the setpoints and reference programs for operation, and the measurement module collects voltage, energy, resistance, etc. and other observations.

An excerpt of the semantic representation of the welding machine and software system is shown in Figure 10. The `WeldingRobot` and `Electrode` classes are the subclasses of `MachinePart` which is linked to the object property *dc:hasPart* to the `WeldingMachine` class, (axiom 7). Moreover, the `WeldingRobot` and `Electrode` are the disjoint classes. Furthermore, The `MachinePart` is connected to `RSWOperation` through *performsA* relation. The `WeldingMachine` and `RSWControlSystem` classes are linked via *hasRSWControlSystem* property.

axiom 7: $WeldingMachine \sqsubseteq \exists hasPart.MachinePart$

$$WeldingRobot \sqcup Electrode \sqsubseteq MachinePart$$

$$MachinePart \sqsubseteq WeldingRobot \sqcup Electrode$$

$$WeldingRobot \sqsubseteq \neg Electrode$$

The welding machine hosts sensors to collect the power, energy, and voltage observations for being recorded in the measurement module. The `WeldingMachine` and `Sensor` classes are linked by the *hosts* relationship. In an operation of RSW, a summary of useful information can be retrieved by using *hasOperationWeldingProgram*,

[6]The Q-Value is a quality indicator that is used to quantify the welding quality. The Q-Value is empirically developed by Bosch Rexroth in the Bosch labs with longtime experience and engineering expertise. A Q-Value of 1 indicates perfect quality.

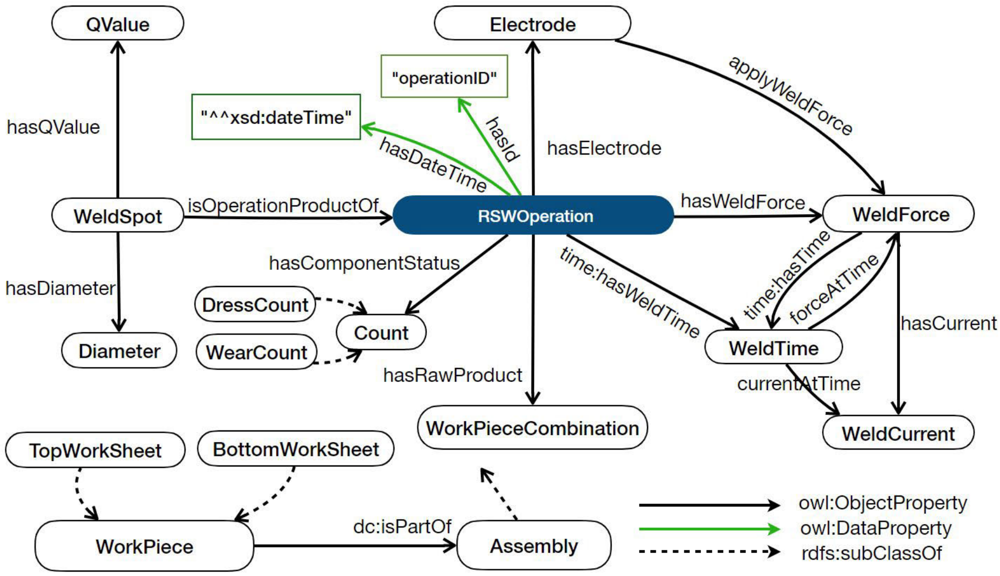


FIGURE 9. RSW operation modelling. The rounded rectangle represent the classes and square rectangle represent the literals.

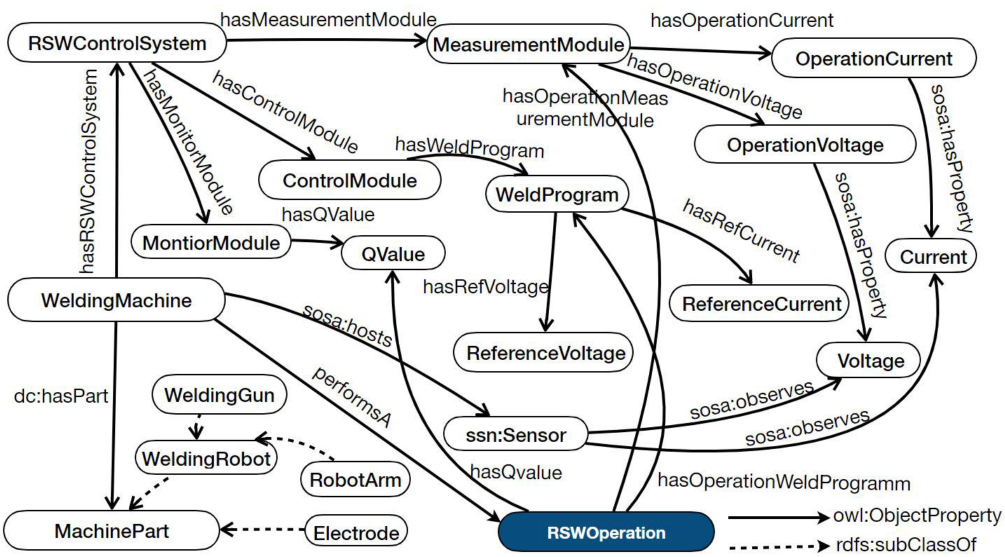


FIGURE 10. An overview of Machine and Software modelling.

hasOperationMeasurementmodule, and *hasQValue* relationships. The Axiom 8 represent that there exists a `MeasurementModule` on the welding control systems to collect operation current property readings.

axiom 8:
$$WeldingMachine \sqsubseteq \exists hasRSWControlSystem.RSWControlSystem \sqcap RSWControlSystem \sqsubseteq \exists hasMeaurementModule.MeasurementModule \exists\ hasMeasurementModule^{-}.RSWControlSystem \sqsubseteq \exists\ hasOperationCurrent.OperationCurrent \sqcap \exists hasOperationCurrent^{-}.(\exists hasMeasurementModule^{-}.RSWControlSystem) \sqsubseteq \exists hasProperty.current$$

D. ELECTRODE

The electrode is an important component of the welding machine used in the `RSWOperation` because its condition (characterised by `WearCount` and `DressCount`) has a significant influence on the welding quality. The object property `hasElectrode` relates the `RSWOperation` with the electrode (Figure 11 and axiom 9). The electrode has two subclasses, namely: `TopElectrode` and `BottomElectrode` that apply force to the workpiece and then pass current to produce resistance creating thus a welding spot. The workpiece has two subclasses of `TopWorkSheet` and `BottomWorkSheet` that interact

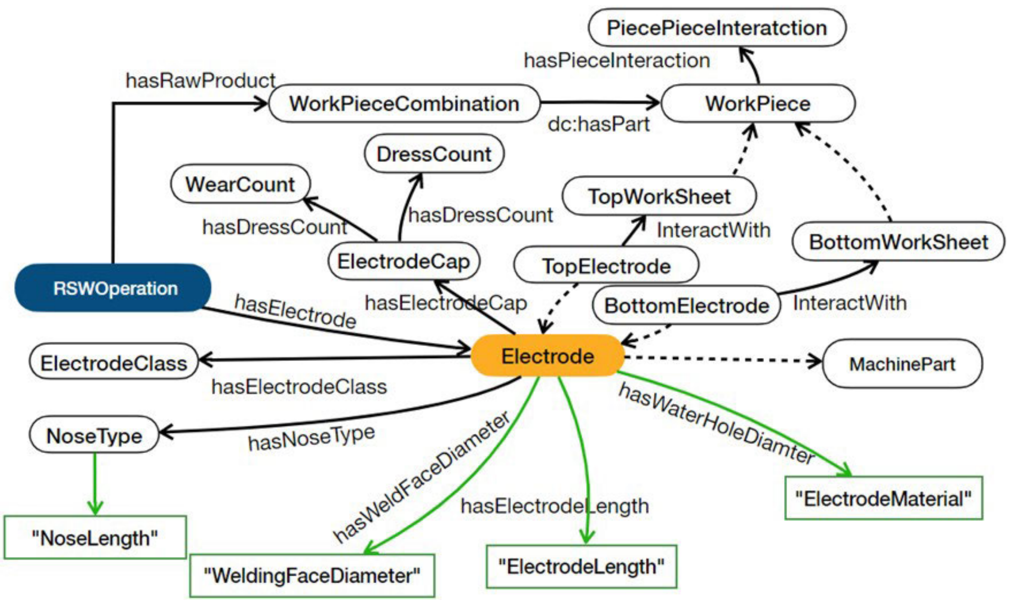


FIGURE 11. An illustration of electrode modelling.

with TopElectrode and BottomElectrode, respectively. The class `PiecePieceInteraction` is used to model interaction properties between the worksheets. For instance, between the two worksheets of RSW, there exist interaction properties such as adhesive, thermal conductivity and electrical conductivity. In this regard, such modelling provides useful information in the operation by representing the `PiecePiece Interaction` and `RSWOperation` through *hasInteraction* relation.

axiom 9: $Electrode \sqsubseteq MachinePart \sqcap Electrode \sqsubseteq \exists hasElectrode^{-}.RSWOperation$

In the `RSWOperation`, the spot welding electrode cap wears and appears as a mushroom, which passes insufficient current and results in inconsistent welds. The electrode dressing procedure is used to restore the original shape of the electrode cap. In order to capture this information, the welding caps have system component status of `WearCount` and `DressCount` that are named as operation count and maintenance count. The electrode comes with a variety of nose configurations which are considered during the design phase of the welding. The electrode face is exposed to extremely high temperatures for a short period of time during the procedure. The electrode temperature is cooled down with water to prevent premature corrosion. The electrode has a water hole of a particular diameter that allows water to flow inside it.

VI. ONTOLOGY EVALUATION

We now discuss the evaluation of RSWO in four dimensions: (1) the use-case use of the Bosch resistance welding process to monitor quality, (2) analyzing for FAIR principles, (3) structural and functional aspects of RSWO with OOPS, and (4) analyzing the attributes richness with OntoMetrics.

A. INDUSTRIAL USE-CASE: QUALITY MONITORING IN RESISTANCE SPOT WELDING

This subsection demonstrates the use-case of a quality monitoring task performed in the resistance spot welding process at Bosch in Germany. The purpose of the industrial use case is to assess the utility and function of RSWO in a truly intelligent manufacturing environment. The remainder of this section gives a comprehensive explanation of the Bosch welding experts, Bosch welding process, welding data and quality monitoring using RSWO.

1) EVALUATION BY BOSCH WELDING AND ONTOLOGY EXPERTS

We now discuss the evaluation of RSWO by domain experts and Ontology Experts (OE). An industrial use-case-based workshop is carried out with the RSW domain experts. The domain experts lack the knowledge about ontology generation and query and as per recommendation, they provided the queries in natural language sentences (Section III-A. The natural language sentences are transformed into competency questions (CQs) that are asked via SPARQL query (Section VI-A4). The CQs in terms of data inspection and diagnostics demonstrated that the ontology developed can be used for the defined use case.

We evaluated our ontology from ontology experts based on the criteria defined by [41]. We provided the ontology file, and documents defining the scope and functional requirements to the ontology experts. The experts gained RSW knowledge from the provided documents. They responded to a series of questions (shown in Table 7). The questions given in the table define the quality criteria related to clarity (1-4), accuracy (5-6), consistency (7), and completeness (8-10) to

TABLE 7. Ontology evaluation by ontology experts. OE indicate the ontology experts. A scale of 1-5 is used to evaluate the ontology criteria where 1 shows strongly disagree, 2 disagree, 3 neutral, 4 agree and 5 strongly agree.

Evaluation criteria	OE 1	OE 2	OE 3
1. Are the annotations of classes sufficient?	3	4	3
2. Are the annotations of classes unambiguous?	4	4	4
3. Are the annotations of properties sufficient?	3	4	4
4. Are the annotations of properties unambiguous?	4	4	4
5. Are [owl:Class]s and [owl:Properties]s well-structured for an RSW domain ontology and do they properly represent the entities?	4	4	4
6. Do the axioms adhere to annotations for the RSW domain?	4	4	4
7. Do the axioms employed convey the concepts intended meaning?	4	4	3
8. Does the ontology cover the necessary concepts required by RSW domain ontology?	4	4	4
9. Does the ontology align to domain-level ontology?	4	5	4
10. Does the ontology reuse term from other ontologies?	4	5	4

TABLE 8. Examples of the dataset attributes, their datatype and short description.

Data Attribute	Data Type	Description
WeldSpot_ID	Integer	Unique identifier of the weldspot
WeldSpot_Diameter	Float	It provide the diameter of the weldspot
WeldSpot_Repetition	Boolean	Indicates whether a weldspot is repeated or not
RSWOperation_ID	Integer	Unique identifier of the resistance spot welding operation
TimeStamp	Date	Timestamp of the date when the operation was performed
Machine_Name	String	Machine that performs the operation Machine_ID
Electrode1_WearCount	Integer	Wear count faced by an electrode during welding
Electrode1_DressCount	Integer	Count of dressing applied to an electrode
Electrode1_WeldForce	Float	Weld force applied by an electrode
Electrode1_SetPoint_Resistance	Float	Reference value of resistance set for Electrode 1

assess ontology context coverage, level of detail, relevance and semantic richness.

We received a score of 4 (Agree) from almost all the OEs. However, the OEs have different views on the clarity of the ontology (questions 1 and 3) and provided a score of 3 (Neutral) which means that there is still some space for improvement. Furthermore, OE 3 think there is some inconsistency in the ontology and gave some specific comments about ontology classes and proprieties (such as has hasControlModule, hasMeasurementModule and hasMonitorModule can be included as part of the RSW control system) and provided a score of 3. OE 2 strongly agreed with the completeness of the ontology and gave a score of 5.

2) BOSCH RSW PROCESS QUALITY MONITORING

Bosch is one of the top world's top manufacturers in the automotive industry. Bosch uses the RSW process to join body parts to manufacture an automotive. In the RSW operation, the surfaces of metal sheets are bonded by the heat gained from the resistance generated by electric current. The body of a typical car can have up to 6000 welding points [16], where metal pieces are connected. Bosch offers a variety of welding solutions, including as software, service, development support, and welding equipment. Other than the Bosch welding plant, these solutions are also adopted by customers all over the world-wide such as BMW, Audi, Ford, and Daimler.

Bosch resistance welding machine and its parts are a tried-and-true way to quickly join hundreds of pieces every hour. To determine and ensure the weld quality (essential to many facets of the vehicle's performance and value) a Q-Value (described in Section V-C) test of the selected components is performed in all operations. Usually, Q-Values are calculated using data collected from production lines. Besides, other important process parameters are monitored to ensure welding quality. Furthermore, the characteristics of the welding robots and their parts are monitored to avoid operation interruptions.

Currently, engineers in Bosch follow a human heuristic approach to monitoring the quality of the welding process for weldspot quantification to avoid RSW operation interruption. However, manually monitoring such a large number of parameters is a complex task. This motivates us to use RSWO to provide access to ontology-based data that facilitates the quality monitoring process for RSW. Using the semantics and domain knowledge of modelling, reasoning and inference of RSWO, the Bosch dataset enhances the quality monitoring process of RSW.

3) BOSCH WELDING DATA

The datasets used in this use-case are acquired from the resistance welding process at Bosch. The datasets are comprised of many formats, such as CSV tables, SQL databases, and text files and inconsistency in variable names and data formats. These datasets contain the attributes that are important to monitor the quality process. Additionally, the data is of two types: namely static and dynamic. As listed in Table 8, for instance, Machine_Name, Machine_ID are static variable its value remains the same in each operation while WeldSpotDiameter, TimeStamp, WeldSpotRepatition and others continue to be dynamic variables and their values change in each operation. The data attributes in Bosch datasets are not interconnected but are co-related with each other semantically. To utilize the data effectively for the monitoring of the welding quality, we have used RSWO to integrate and access the data. The data to ontology was manually mapped using the RSWO terms that integrated the data from different sources into uniform data format [42].

4) ANSWERING THE COMPETENCY QUESTIONS: BOSCH DATA-BASED MONITORING THE WELDING PROCESS

We now demonstrate several examples of using SPARQL queries to answer the competency questions provided by the experts for quality monitoring.

Example 1: Provided the CQs in Table 2, we considered CQ1 from the data inspection category to perform basic monitoring tasks for quality welding. This demonstrates the efficiency and usefulness of the RSWO in monitoring and tracking the critical to process parameters of the production resources and processes. The query retrieves the welding force, voltage, current and power values during the particular operations upon successful execution as is shown in Figure 12.

Example 2: In the context of the monitoring welding process, the query (CQ 6) from the diagnostics is adopted. The query mentioned in Figure 13 is executed to reason about the Q-Values of the weld spot with higher than the threshold in any operation. In Bosch weld production, the increase in the Q-Value is due to the increase in the voltage and power that are considered critical to process parameters. This alternatively raises the spatters occurrence on the near parts of the worksheets. In this context, the query retrieved the critical to process parameters, and the results returned are shown in Figure 13. The query has used the `FILTER` keyword to monitor all the Q-Value of the RSW operations and *:hasQValueActual* greater than 1.20. The `OPTIONAL` keyword is binding in this query that enables us to query for data but prevents the query from failing when the requested data is not there. After query processing, both optional and non-optional information is provided. The keyword `GROUP BY` grouped the query results where its order sequence is established by the clause `ORDER BY`.

The proposed query fetched three RSW operations that have a Q-Value greater than the threshold. The voltage and power parameters are also analysed at the same time and it can be observed from Figure 14 that as voltage and power raises, the Q-Value also increases. A weldspot produced with such high values of critical to process parameters can halt the production line and thus can badly affect the parts of the welding machine.

Example 3: Furthermore, in relation to monitoring the welding quality, the spatters that occurred during the operation are usually observed. The occurrence of the spatters badly affects the quality of welding. The spatters occurrence indicates the production line engineers to adjust the critical to process parameters such as weld force level, squeeze time, voltage, current, etc. We utilized CQ7 to find the occurrence of spatters during a particular time. The query along with its result is shown in Figure 15. The `FILTER` keyword narrowed down our search between a given particular time. Thus, the above examples demonstrate the usability of RSWO modelling for retrieving the integrated data and information within the RSW domain.

B. EVALUATION ON FINDABLE, ACCESSIBLE, INTEROPERABLE, REUSABLE (FAIR)

We now discuss the evaluation of RSWO on Findable, Accessible, Interoperable, and Reusable (FAIR) principles. FAIR principles are a set of guidelines [43] that facilitate to build of a coherent and machine-friendly data environment. Reference [17] developed O'FAIRe[7] methodology to encourage ontologies, vocabularies and semantic artefacts compliance with the FAIR guiding principles. It includes 15 foundational FAIR principles for ontologies and is harmonized with state-of-the-art FAIRness assessment initiatives. The first term *Findable* in the FAIR makes sure that ontology is described with sufficient metadata that can be searched in a registered repository with a persistent and unique identifier, the second term *Accessible* assess that the ontology can be retrieved in an implementable protocol. The third term *Interoperable* evaluates that the ontology can be processed in a standard way by other stakeholders. The final *Reusable* term assesses in terms of explicit licences and usage information of the ontology for humans and machines. The O'FAIRe methodology assessed the RSWO using 61 FAIR questions. We have adopted the O'FAIR methodology as it is being used by AgroPortal[8] and IndustryPortal[9] to assess ontologies for FAIR score.

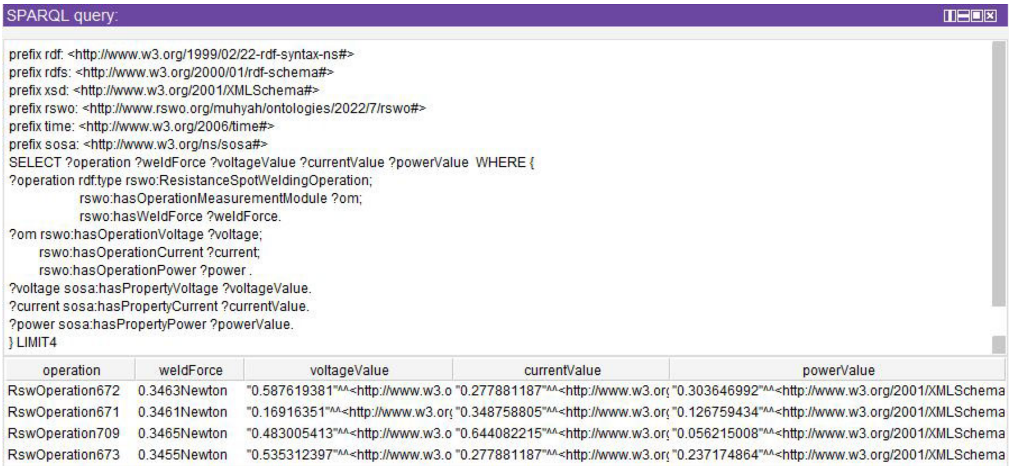
We evaluated RSWO in line with the O'FAIRe methodology and obtained a total FAIR score of 271 out of 478 which is 56.0%. The RSWO FAIR score against the 15 foundational FAIR principles is shown in Figure 16. Moreover, to make a comparison with other relevant ontologies, we have shortlisted all ontologies with FAIR score greater than 230 from Industry Portal Table 9.

It can be observed from the table that EXTRUONT [44] is the only ontology which has a higher FAIR score (272.13) than RSWO (271.00). In comparison with RSWO, the rest of the ontologies have lower FAIR scores. The RSWO has a high Findable principle score in contrast to other ontologies which is 75 out of 113 which is 66.37%. The Accessible principle score of RSWO is equal to other ontologies. The EXTRUONT has a high Interoperable principle score of

[7]https://github.com/agroportal/fairness

[8]http://agroportal.lirmm.fr/ontologies

[9]Industry Portal (http://industryportal.enit.fr/) is an online portal for Industrial manufacturing ontologies. It is supported by the OntoCommons project that encourages the researcher to deploy their ontologies designed for Industries especially manufacturing.

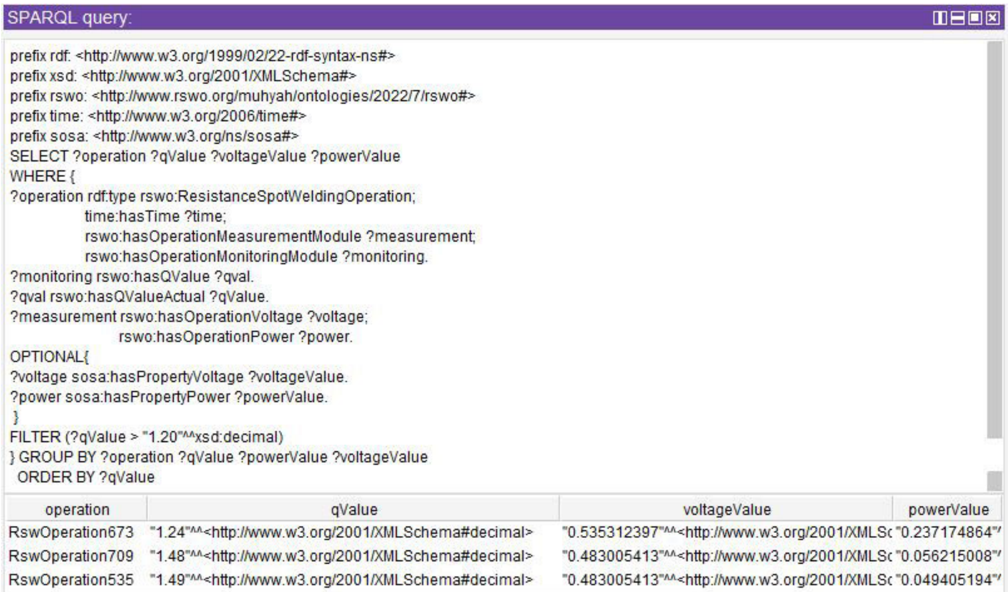


SPARQL query:

```
prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix xsd: <http://www.w3.org/2001/XMLSchema#>
prefix rswo: <http://www.rswo.org/muhyah/ontologies/2022/7/rswo#>
prefix time: <http://www.w3.org/2006/time#>
prefix sosa: <http://www.w3.org/ns/sosa#>
SELECT ?operation ?weldForce ?voltageValue ?currentValue ?powerValue  WHERE {
?operation rdf:type rswo:ResistanceSpotWeldingOperation;
           rswo:hasOperationMeasurementModule ?om;
           rswo:hasWeldForce ?weldForce.
?om rswo:hasOperationVoltage ?voltage;
     rswo:hasOperationCurrent ?current;
     rswo:hasOperationPower ?power .
?voltage sosa:hasPropertyVoltage ?voltageValue.
?current sosa:hasPropertyCurrent ?currentValue.
?power sosa:hasPropertyPower ?powerValue.
} LIMIT4
```

operation	weldForce	voltageValue	currentValue	powerValue
RswOperation672	0.3463Newton	"0.587619381"^^<http://www.w3.o	"0.277881187"^^<http://www.w3.or	"0.303646992"^^<http://www.w3.org/2001/XMLSchema
RswOperation671	0.3461Newton	"0.16916351"^^<http://www.w3.or	"0.348758805"^^<http://www.w3.or	"0.126759434"^^<http://www.w3.org/2001/XMLSchema
RswOperation709	0.3465Newton	"0.483005413"^^<http://www.w3.o	"0.644082215"^^<http://www.w3.or	"0.056215008"^^<http://www.w3.org/2001/XMLSchema
RswOperation673	0.3455Newton	"0.535312397"^^<http://www.w3.o	"0.277881187"^^<http://www.w3.or	"0.237174864"^^<http://www.w3.org/2001/XMLSchema

FIGURE 12. Inspecting the critical to process parameters data CQ1.



SPARQL query:

```
prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix xsd: <http://www.w3.org/2001/XMLSchema#>
prefix rswo: <http://www.rswo.org/muhyah/ontologies/2022/7/rswo#>
prefix time: <http://www.w3.org/2006/time#>
prefix sosa: <http://www.w3.org/ns/sosa#>
SELECT ?operation ?qValue ?voltageValue ?powerValue
WHERE {
?operation rdf:type rswo:ResistanceSpotWeldingOperation;
           time:hasTime ?time;
           rswo:hasOperationMeasurementModule ?measurement;
           rswo:hasOperationMonitoringModule ?monitoring.
?monitoring rswo:hasQValue ?qval.
?qval rswo:hasQValueActual ?qValue.
?measurement rswo:hasOperationVoltage ?voltage;
             rswo:hasOperationPower ?power.
OPTIONAL{
?voltage sosa:hasPropertyVoltage ?voltageValue.
?power sosa:hasPropertyPower ?powerValue.
 }
FILTER (?qValue > "1.20"^^xsd:decimal)
} GROUP BY ?operation ?qValue ?powerValue ?voltageValue
 ORDER BY ?qValue
```

operation	qValue	voltageValue	powerValue
RswOperation673	"1.24"^^<http://www.w3.org/2001/XMLSchema#decimal>	"0.535312397"^^<http://www.w3.org/2001/XMLSc	"0.237174864"
RswOperation709	"1.48"^^<http://www.w3.org/2001/XMLSchema#decimal>	"0.483005413"^^<http://www.w3.org/2001/XMLSc	"0.056215008"
RswOperation535	"1.49"^^<http://www.w3.org/2001/XMLSchema#decimal>	"0.483005413"^^<http://www.w3.org/2001/XMLSc	"0.049405194"

FIGURE 13. Result returned by CQ6 to analyze Q-Value, voltage value and power value.

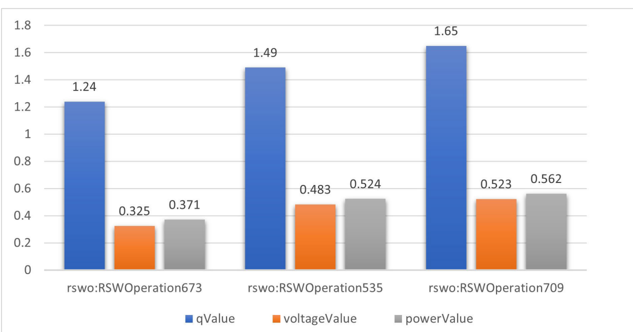


FIGURE 14. Retrieved Q-Value (dimensionless), voltage (Volt) and power (Watt) (anonymized) values against RSWoperation673, RSWoperation535 and RSWoperation709 for CQ6.

63.13 out of 109 while RSWO has an acceptably low Interoperable principle score of 54 and comes second in the list for interoperability score. Other ontologies have low Interoperable score than RSWO. The Reusable principle score of the RSWO ontology is 50 which is acceptably low than EXTRUONT and FUNSTEP.[10] The RSWO has a high Reusable principle score to that of SAREF4INMA [45] and SCOR. The IOF-Maintenance (IOF-MAINT.) [46], IMAMO [47] and SIMPM has a low score of Reusable principle in contrast to RSWO. About comparison with RGOM, RSWO has a higher FAIR score. Due to the reason that the RSWO is not yet included in a specific community, therefore, it received Score:0.0 for the FAIR principles question (*"R1.3Q2": Is the ontology included in a specific community set or group?*). The metadata of the RSWO provides rich information that gives high score than other ontologies.

[10]http://www.funstep.org/ontology/

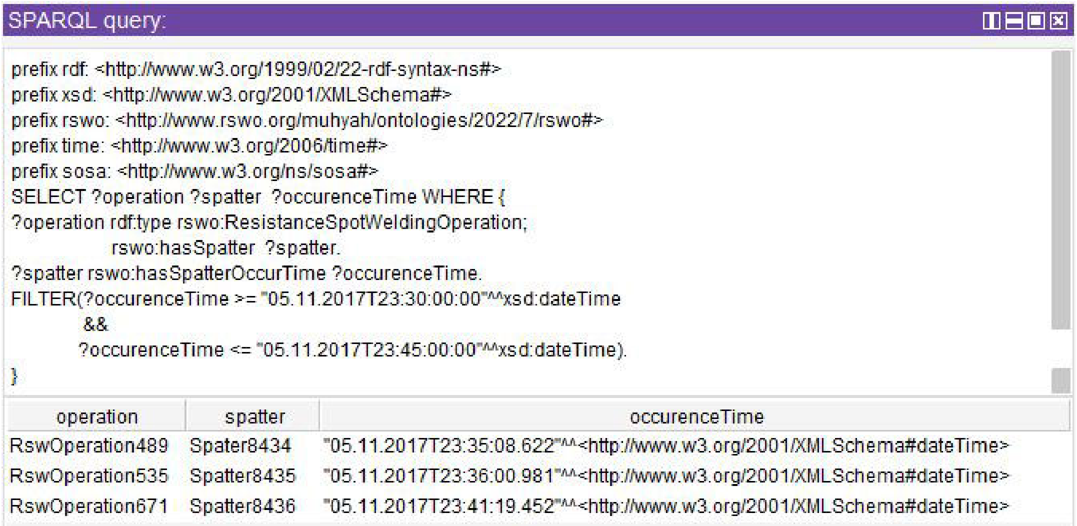


FIGURE 15. Retrieved results of spatters and its occurrence during particular time by utilizing CQ7.

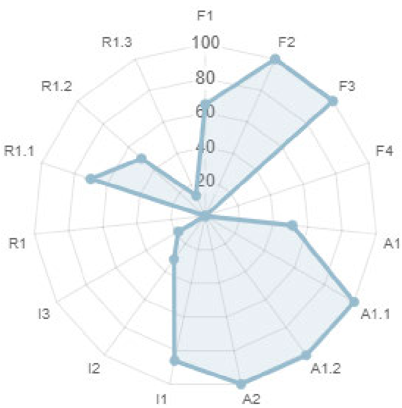


FIGURE 16. FAIR result of RSWO.

C. OOPS!

The Ontology Pitfall Scanner (OOPS!) assesses the ontology in its creation process by looking at the design imperfections from a list of 41 recurring flaws, which are categorized as minor, important and critical. The OOPS! can identify the majority of them (33 out of 41 dangers) semi-automatically. The OOPS tool has been used frequently to find minor, important, and critical changes.

The RSWO assessment with OOPS yields some minor pitfalls that have no bearing on the ontology's reasoning, consistency or/and applications. The issue of *unconnected ontology elements*, *several classes with same labels*, and *missing domain and range* reported are mainly due to the inheritance of SSN ontology terms and relations. The assessment of the RSWO results by OOPS! is shown in Figure 17. Furthermore, the OOPs tool assesses criteria such as *clarity*, *completeness*, *conciseness* and *consistency*. The criteria of how the RSWO applies them in line with an explanation, are listed below.

- **Clarity:** The ontological terms defined to represent the classes, concepts, and relations of all the modules, contain unambiguous names, and annotations. The annotations aid in the readability by humans to avoid uncertainty and difficulty during the insertion of data elements.
- **Completeness:** The ontology is capable to answer all competency questions as defined by the industry experts, correctly describing the domain for which the ontology was created.
- **Conciseness:** The industry knowledge represented by ontology is gathered in line with the sources, particularly those in the domains of electrodes, welding materials and processes, and enterprise and their production lines, thus eliminating irrelevant information.
- **Consistency:** The Fact++[11] reasoners have been applied to find inconsistencies in the RSWO. Accordingly, the reasoner has not found any inconsistencies in the developed ontology.

D. OntoMetrics

To assess RSWO, we adhered to the guidelines in [48]. The RSWO is assessed with the OntoMetrics [49], to reflect some notions of ontology richness with five metrics (details follow in next paragraph). There is no public available (to our best knowledge) resistance spot welding ontology that we can directly compare with. Table 10 contains a subset of the metrics computed by OntoMetrics that highlight the ontology's most intriguing domain coverage features.

- *Attribute richness:* It calculates the average number of attributes (slots) per class, indicating the quality of the ontology design and the quantity of information that can be contained in the instance data. The RSWO has an attribute richness of 1.613929.

[11] http://owl.man.ac.uk/factplusplus/

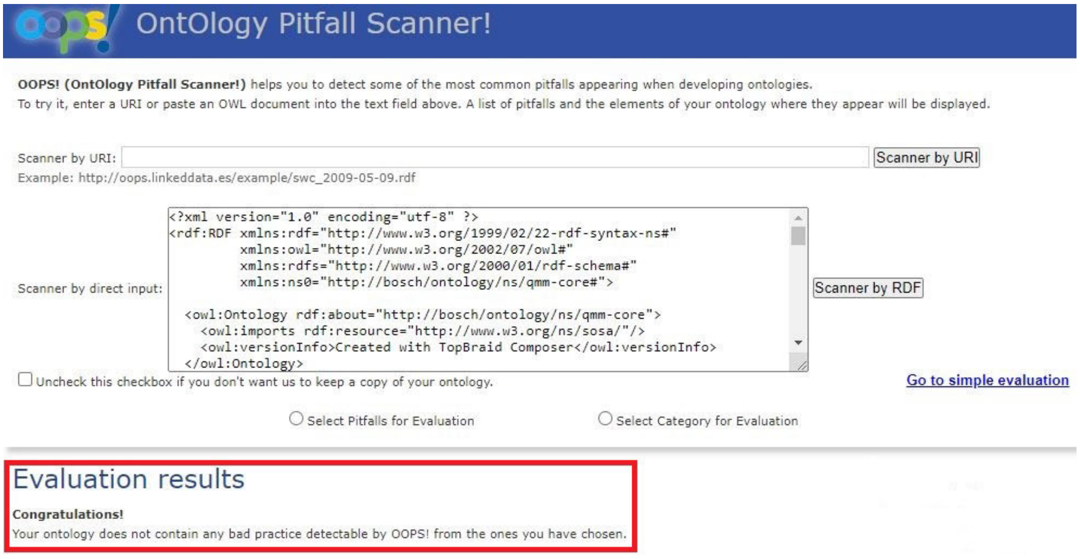


FIGURE 17. OOPs assessment shows RSWO does not contain any bad practice detectable by OOPS!

TABLE 9. FAIR score with the industry portal ontologies in descending order. The results show our RSWO has relatively high scores compared to other state-of-the-art ontologies.

Ontology	Findable	Accessible	Interoperable	Reusable	TotalScore
EXTRUONT	64(56.63%)	92(81.41%)	63.13(57.91%)	53(37.06%)	272.13(56.0%)
Ours (RSWO)	75(66.37%)	92(81.41%)	54.00(49.54%)	50(34.96%)	271.00(56.0%)
RGOM	74(65.48%)	101(89.38%)	48(44.03%)	44(30.76%)	267.00(55.0%)
SAREF4INMA	60(53.09%)	92(81.41%)	51.13(46.9%)	48(33.56%)	251.13(52.0%)
SCOR	58(51.32%)	90(79.64%)	45.13(41.4%)	48(33.56%)	241.13(50.0%)
FUNSTEP	54(47.78%)	92(81.41%)	42.00(38.53%)	53(37.06%)	241.00(50.0%)
IOF-MAIN.	51(45.13%)	90(79.64%)	48.00(44.03%)	46(32.16%)	235.00(49.0%)
IMAMO	58(51.32%)	92(81.41%)	41.00(37.61%)	43(30.06%)	234.00(48.0%)
SIMPM	56(49.55%)	92(81.41%)	45.75(41.97%)	39(27.27%)	232.75(48.0%)

TABLE 10. Evaluation of RSWO on OntoMetrics.

Metric	RSWO
Attribute richness	1.613929
Inheritance richness	0.973007
Relationship richness	0.495000
Average population	4.981892
Class richness	0.830357

- *Inheritance richness:* The term inheritance richness refers to the average number of subclasses per class and describes the distribution of information along the multiple levels of the ontology's inheritance tree. The value of 0.973007 highlights that the RSWO covers a good range of concepts.
- *Relationship richness:*It indicates the variety of relational types and is calculated as the ratio of (non-inheritance) relationships to all relationships in the ontology. OntoMetrics tool reported a 0.495000 value for relationship richness.
- *Average population:* It provides information about the quality of the ontology population which corresponds to the ratio of instances to classes. The RSWO has an average population of 4.981892.
- *Classes richness:* It represents the distribution of instances among classes. The overall number of classes is compared to the number of RSWO classes that have instances and provided an overview of how well the knowledge base uses the knowledge represented by the schema classes. The class richness of RSWO is 0.830357.

VII. CONCLUSION AND OUTLOOK

In the trend towards smart automation of Industry 4.0, unprecedented amounts of data are collected in the resistance spot welding process, a typical automatic manufacturing process. Ontologies are essential in various aspects: the data challenges of volume and variety, as well as the applications such as domain understanding, data understanding, and data integration. Past work missed crucial concepts that are important for real-world industrial usage and have not made the ontologies publicly available (to our best knowledge). To address these issues, this paper presents Resistance Spot Welding Ontology (RSWO) and makes it publicly available. RSWO combines three sources of knowledge: industrial expert knowledge at Bosch; terminology from the international standard, ISO-14327 and ISO-14373; and existing relevant ontologies. The RSWO includes important concepts such as *RSWOperation*, *RSWControlSystem*, *Electrode*, which are exemplified with queries on industrial datasets collected from running production lines. The development of RSWO was performed in an industrial environment. The RSWO is assessed with an industrial use case, domain and ontology experts, and established methodologies of O'Faire, OOPS! and OntoMetrics, which show the benefits of RSWO in aspects of real usage as well as its Findability, Accessibility, Interoperability, and Reusability, quality and richness. Moreover, this methodology can be extended to other welding scenarios.

As future directions, there is a wide range of topics to be explored: (1) *Commons for Industry* that includes a series of commonly agreed artefacts, methodologies, and best practices, such as a general and standardized ontology for all manufacturing processes, frameworks for sharing data, procedures of cross-domain innovation and strategy negotiation; (2) *Industrial Feedback for Facilitating Research*, the increased research, development and deployment of ontologies and knowledge graphs of industry problems will, in turn, inspire many impactful and challenging research questions that boost research and its interaction with industry, ranging from semantics-based data interoperability, metadata-based or content-based dataset search to neuro-symbolic reasoning for graph data.

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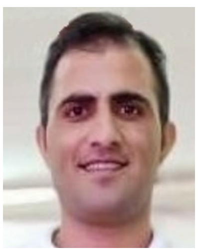

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