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Core Domain Ontology for Joining Processes to Consolidate Welding Standards

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Abstract

Extensive advancement in the field of the joining science has led to the development of a wide range of joining processes and techniques. Welding is one of the most widely used joining processes. Various standards have been developed to regularise welding processes and ensure manufacturing consistency. However, there are various inconsistencies and incoherencies in terms of process categorisation within and across the welding standards. In this paper, investigations are undertaken to understand the limitations and issues with current welding standards from the point of view of semantic inconsistency. The inadequacy of text based definitions of welding concepts for interoperability has been revealed. To address the issues, in this paper, Core Domain Ontology for Joining Processes (CDOJP), that can semantically categorise joining processes to reconcile the semantic inconsistency issues, is developed. A formal ontological approach using Web Ontology Language (OWL) is used to define the ontology formally. The generic nature of the proposed ontology allows it to be applicable for all types of joining processes. The proposed ontology is then consolidated to the welding standards so that semantic inconsistencies can be effectively resolved. This research is validated for semantic inconsistency resolving in an industrial environment via collaboration with one of the largest aero engine manufacturing companies.

Keywords: Ontology, Joining, Welding, Interoperability

1. Introduction

Manufacturing is one of the key sectors in the world economy. Information during product development processes is structurally held in product and manufacturing models [1-5]. Large multi-national manufacturing organisations tend to work in silos which heavily contribute towards diversified product and manufacturing models. This brings interoperability issues of information in different application domains, leading to high cost for resolving problem and consolidation. Interoperability problems have been estimated to cost about $1 billion annually to the automotive sector of US [6] and $15.8 billion to their capital facilities [7]. It has been reported that about $31.5 billion is spent annually by the Fortune 500 companies to overcome interoperability problems [8]. Among the interoperability issues, about 70% of the interoperability costs have been reported to be spent on reconciliation of semantic inconsistencies, which is referred as the ability to seamlessly exchange information across systems [9-11]. Therefore, it is essential for product and manufacturing models to be devoid of semantic inconsistencies for consistent knowledge capture and sharing among different application domains to ensure interoperability.

The interoperability problems can potentially be overcome through standards. For example, various standards for welding have been developed to support interoperability between welding and design domains. Standards also attempt to regularise welding processes as there are multiple categories based on material conditions and applications. The International Organisation for Standardisation (ISO) community has developed the ISO/TR 25901 Standards as agreed global references for welding. Although the ISO is global in scope, there are various national organisations and committees that have developed their own standards to meet local industrial requirements. For example, the American Welding Society (AWS) has developed its own standards for American industries, while the British Standard Institution (BSI) has done the same for the UK. For the standards, research has shown that they have semantic inconsistency issues [12]. The standards can achieve their desired goal of being a global reference to support wider industrial requirements, only if they are devoid of any semantic inconsistency across themselves.

The semantic inconsistency issues of manufacturing centric standards were investigated in [12]. The subjective interpretation of their concepts was highlighted in [13-15]. Such issues are usually resolved by 'domain experts' who can agree on correct and consistent interpretation. However, this is inefficient and error-prone, demanding ICT-based approaches and systems to be imperative. Ontological approaches for semantic inconsistencies and reconciliation were addressed by various researchers. Assembly Reference Ontology (ARO) was developed to address the interoperability between the domains of design and assembly [16], but the developed core concepts were found to be overly generic and falls short to address the specific domain of welding. Although the Design for Manufacturing (DFM) ontology developed in [17] was for addressing the welding domain, but it fails to provide a structure that can semantically categorise the welding processes. Similar limitation was found in the ontology developed by [18]. Manufacturing Core Concepts (MCCO) was created in [19] to share knowledge between machining and design. However, it was found to be highly constrained to these two domains and devoid of any welding related concepts. An Adaptive Holonic Control Architecture for Distributed Manufacturing Systems (ADACOR) ontology was designed in [20] to address the production planning and scheduling without looking into the specific domain of welding. Similarly, the product ontology developed in [21] and the manufacturing ontology proposed in [22] was found to be generic as well. They fail to address the specificity required to overcome the semantic inconsistency in the welding domain and the corresponding standards. The above analysis on prior articles highlight that there is no investigation to understand semantic inconsistencies issues and their impacts on interoperability for welding.

This paper is aimed at developing an innovative ontology to address the above issue. In the paper, the research firstly investigates the semantic inconsistency issues in welding standards. Secondly, a solution in the form of Core Domain Ontology for Joining Processes (CDOJP) is proposed to capture the semantics of the welding concepts. The semantics of the core concepts within CDOJP are further adapted as per the definitional requirements of the welding specific standards to resolve the semantic issues within and across them. Web Ontology Language Description Logic (OWL DL) is then exploited as the ontological formalism methodology for this research. It is further used for the formalisation of the proposed CDOJP as well as for consolidation of welding standards. Finally, the research is validated in an industrial environment from one of the largest aero engine manufacturing companies.

This paper is organised as follows: Section 2 describes the standardisation within the welding domain, as well as the requirements for using an ontological approach in representing the standards for interoperability. Section 3 portrays the proposed semantically enriched CDOJP. Section 4 explains the formalisation of the proposed ontology as well the consolidation of the welding standards. Section 5 explains the experimental verification of semantic inconsistency using the developed approaches. Section 6 concludes the work with description of the future and ongoing work.

2. Requirements for Consolidating Welding Standards

2.1 Standardisation for Welding

This section reports on the breadth of welding standards before investigation into their semantic inconsistency and interoperability issues. The scope of the ISO welding committee is for "*Standardisation of welding, by all processes, as well as allied processes; these standards include terminology, definitions and the symbolic representation of welds on drawings, apparatus and equipment for welding, raw materials (gas, parent and filler metals) welding processes and rules, methods of test and control, calculations and design of welded assemblies, welders' qualifications, as well as safety and health.*" [23]. It signifies that the committee looks after all the regularisations as well as unveiling of the best practices within the welding domain.

Even though ISO defines the international welding standard ISO/TR 25901, there are several other regional standards developed by different welding communities. Table 1 shows the major standardisation bodies involved in development of welding standards along with the corresponding technical committees involved. Manufacturing companies prefer a multi-standard based approach to address various industrial requirements. However, the considerably large number of standards available poses a problem for interoperability owing to a lack of compatibility of the terms used as they are defined in different ways even though their uses in practices could be the same or similar. This paper will mainly focus on the accurate capture of the semantics of the core terms used in the standards and overcome their semantic inconsistency.

Table 1: Major welding standardisation bodies and standards

Organisation	Level of Authority	Jurisdiction	Welding Technical Committee (TC)	Sub Committee for Vocabulary (SC)	Standard Name
International Standard Organisation (ISO)	International	Worldwide	ISO/TC 44	ISO/TC/44 SC7	ISO/TR 25901-1:2016, ISO/TR 25901-2:2016, ISO/TR 25901-3:2016, ISO 25239-1:2011
European Committee for Standardisation (CEN)	Continental	European Union	CEN/TC 121		PD CEN/TR 14599:2005
American Welding Society (AWS)	National	America	AWS A2	AWS A2B	AWS A3.0M/A3.0:2010
British Standards Institution (BSI)	National	United Kingdom	BS WEE/1		BS 499-1:2009

2.2 Semantic Inconsistency in Welding Standards

For the welding standards reported earlier, there are various issues of semantic incontinency [24], which are required to be resolved in order to support interoperability. This research will focus on text based semantic inconsistency, and the investigations are from two perspectives: (1) inconsistencies within the same standards, and (2) inconsistencies across different standards.

The terms and definitions in the welding standards were found to be highly textual, making them open to human interpretation and therefore inefficient and error-prone for interoperability. The textual nature and the subjective interpretation of the standards are corroborated by the following example:

Welding is defined in AWS as *"A joining process that produces coalescence of materials by heating them to the* *Welding Temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal"* (AWS A3.0).

This definition introduces the term *Welding Temperature*, which is not explained in the standard and open to any interpretation. *Welding Temperature* can be perceived as any temperature. This raises ambiguity or misinterpretation of the various welding processes as it relies on every individual's perception on this term. This will further affect the categorisation of welding processes. The commonly believed understanding of *Welding Temperature* is that it is the melting temperature of the substrate material. However, agreeing on this definition the categorisation of the *Solid State Process* as a welding process is semantically inappropriate. The definition of *Solid State Process* in AWS A3.0 is shown in Figure 1. According to the definition, there is no melting involved in the process that is a contradiction of its enlistment as a welding process. Therefore, without the clarity on the semantics of *welding temperature*, there will be confusion with regards to categorisation of other welding and other joining processes. Therefore, it is essential to capture the semantics of welding temperature for each specific welding process. This is just one example of how text based semantics can create problems for interoperability.

Fusion Welding (AWS A3.0): *"Any welding process that uses fusion of the base metal to make the weld."*
Solid State Welding (AWS A3.0): *"A group of welding processes that produce coalescence by the application of pressure without melting any of the joint components."*

Figure 1: Definition of fusion & solid state welding in AWS

Another example is from the ISO welding standard. The standard does not use the term *Welding Temperature* but it shows ambiguity in terms of interpretation as well. For example, the definition of *Welding* in the ISO standard is: *"Joining process in which two or more parts are united producing a continuity in the nature of the workpiece material(s) by means of heat or pressure or both, and with or without the use of filler material"* (ISO – TR 25901-1) (CEN – TR 14599 [EN 1792]) (BS 499-1).

This definition does not describe the condition of the substrate material during the process. Hence, its interpretation might lead to erroneous classification of not only the welding processes but also the other joining processes. Depending on the standard implemented for industries, it will recognise and interpret the semantics for that particular standard. Hence, systems implemented with AWS and ISO semantics will struggle to share knowledge with each other.

In the following, text based semantic inconsistencies within the same standards and across different standards will be further elaborated.

Inconsistencies within the same standard

Investigations have found inconsistencies within the same standards themselves. For example, in the AWS A3.0 standard, the categorisation of the *Resistance Spot Welding* and *Resistance Seam Welding* processes is found to have issues. The standard classifies both of the processes as *Fusion Welding* as well as *Solid State Welding*, which is clearly a violation of the fundamental semantics of their definition as illustrated in Figure 2. The key attribute that differentiates the two processes is the condition of the substrate material during the joining process itself. This fundamental difference prevents the categorisation of the same process in two different categories as it violates the inherent semantic rationale of the definitions.

Fusion Welding (ISO /TR 25901): *"Welding without application of external force in which the faying surface(s) has (have) to be molten; usually, but not necessarily, molten filler metal is added."*
Welding with Pressure (ISO /TR 25901): *"Welding in which sufficient outer force is applied to cause more or less plastic deformation of both the faying surfaces, generally without the addition of filler metal"*

Figure 2: Definitions of fusion & welding with pressure in ISO

Moreover, in both AWS and ISO standards, *Braze Welding* has been classified as a *Brazing* process. However, the process does not involve any capillary action, which is a radical requirement for *Brazing*. Furthermore, the process does not involve melting of the substrate material thereby casting scepticism over the process being termed as *Welding*. The interpreted semantics of the processes might classify it as a *Solid State Welding* process as well. Hence, this categorisation is debatable and inappropriate for interoperability due to the prevalent inconsistencies.

Inconsistencies across different standards

Similar shortcomings are found across multiple standards. For example, the ISO standards denote *Solid State Welding* as *Welding with Pressure*. It is entitled to encompass all the processes where the coalescence occurs due to pressure. However, some of the processes which have been classified within this category are also categorised as the *Fusion Welding* process in the AWS standard. The definitions of the processes in ISO & AWS are depicted in Figures 1 and 2. Although the definitions are not entirely identical, the overarching theme of them is similar. The varying categorisation across multiple standards is depicted in Table 2.

This portrays the violation of semantics of the definitions across them. The standards are mutually incoherent, further compelling customers to follow any particular standard in a multinational environment.

Table 2: Inconsistencies across different standards

Process	ISO		AWS	
	Fusion Welding	*Welding with Pressure*	*Fusion Welding*	*Solid State Welding*
Percussion		X	X	
Projection		X	X	
Flash		X	X	
Resistance Spot		X	X	X
Resistance Seam		X	X	X

The investigation has highlighted the issues faced for welding interoperability using these standards. It was understood that some inconsistencies in the standards are self-contradictory, some are categorised wrongly and some are mutually non-reconcilable in their current form. This makes it more evident that it is imperative to have a more rigorous, consistent and computer interpretable categorisation and definition of welding concepts.

These concepts are, however, required to be defined more rigorously at a generic level for all types of joining processes that can further constrict to welding concepts. This is achieved through an ontology for joining processes, described in Section 3. The need to capture knowledge at different levels of abstraction enforces the need to have concept definition from a generic to specific welding level. This will be discussed in Section 4.

3. Core Domain Ontology for Joining Processes (CDOJP)

Ontological approaches are useful tools for information sharing and knowledge management to support interoperability [25]. One of the most quoted definitions of ontology states that it is an "explicit specification of conceptualisation" [26] with several others provided by [27-35]. Ontologies define a common semantic base, through which knowledge and information can be shared seamlessly. Furthermore, it resolves semantic mismatches [36-38]. Key steps required in creation of ontology are stated below:

a) Defining key concepts for the domain
b) Specifying the hierarchical level in which these concepts reside, and the relationships between the concepts
c) Identifying the inconsistencies from the above relationships

For this research, Core Domain Ontology for Joining Processes (CDOJP) will be developed, to establish a foundation for consolidating welding processes to resolve semantic inconsistency as described in Section 4. The following will illustrate the modelling process of CDOJP.

3.1 Key Concepts and Overview of CDOJP

Traditionally, ontologies has been categorised as foundation, core (reference) and domain ontologies [39]. The specificity of the concepts varies from being vastly generic at the foundational level to highly specific at the domain level. The concepts belonging to the core (reference) ontologies have a neutral viewpoint as they are claimed to be neither as generic as the foundation concepts nor as highly specific as the domain concepts.

Figure 3 shows the different concepts with varying depth of meanings within the core concept level. It can be seen that from the semantic neutral viewpoint of the concepts at the core concept level, there is a challenge for capturing the detailed knowledge with high granularity. For example, the concepts *Process* and *Manufacturing Process* both reside at the core concept level but they have varying depth of semantics as one has more specific realm than the other. Similarly there are other concepts within the same level which has different specificity. This can potentially lead to improper knowledge capture at a higher granularity. Hence, it is crucial to capture the variations for ensuring seamless and consistent knowledge sharing. Multiple levels of specialisation are therefore proposed to capture this variation of meanings through the evolution of the concepts from the very generic to the more specific domain of welding. Figure 4 illustrates such multiple levels of representing the *Process* concept from its foundation to the domain level, which is explained below.

The generic semantics of the concept *Event* has a wide spectrum of application and acts as the foundation for the *Process* concept specialisation. In this way the foundation level is specialised into the Core Concept level, which has Generic Core Concepts and Product Lifecycle Core Concepts as its sub layers. *Process* concept forms part of the generic core concepts as its semantics are prevalent across different processing and manufacturing domains. It is further specialised into *Manufacturing Process*, which is a product lifecycle core concept for addressing the semantics of multiple product lifecycle domains. The Core Concept level is specialised into Domain Concept level where the proposed CDOJP resides. Similar to the previous level, this has Domain Core Concepts as one of its sub layer for concepts generic to a particular domain. Domain Specific Concepts is it's another sub layer for concepts that are highly specific and semantically constrained to only one particular domain. The *Manufacturing Process* evolves through these layers as *Assembly Process* and *Welding* concepts respectively. The concepts have provisions further develop application specific ontologies.

In summary, the above concepts are defined below:

a) Foundation Concepts – Concepts that are vastly generic for any application, e.g., *Object*

b) Core Concepts
   i. Generic Core Concepts – Concepts which are generic, irrespective of the type of applicable industry, e.g., *Process* is a concept that as its utilisation in the mechanical, manufacturing, software industries, etc.
   ii. Product Lifecycle Core Concepts – Concepts which are generic across multiple Product Lifecycle domains, e.g., *Material* which has its applicability across the entire product lifecycle

c) Domain Concepts
   i. Domain Core Concepts – Concept which are generic for a particular domain. E.g. *Mating Configuration* is generic for the entire domain of joining
   ii. Domain Specific Concept Level – Concepts which are constrained to a particular domain. E.g. *Welding* which is one specific joining process

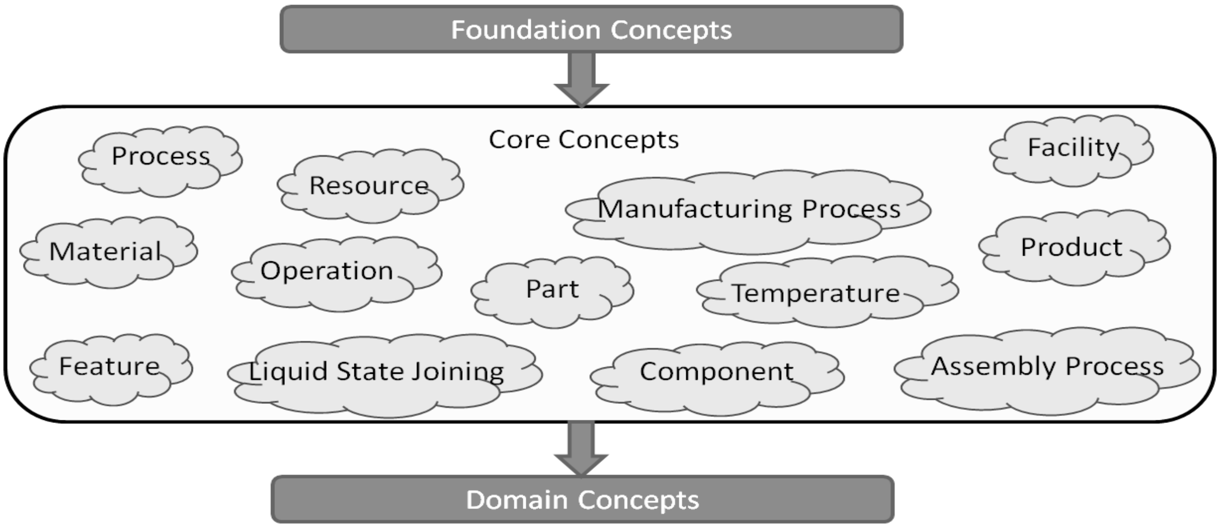


Figure 3: A challenge to represent varying depths of meaning within the core concepts level

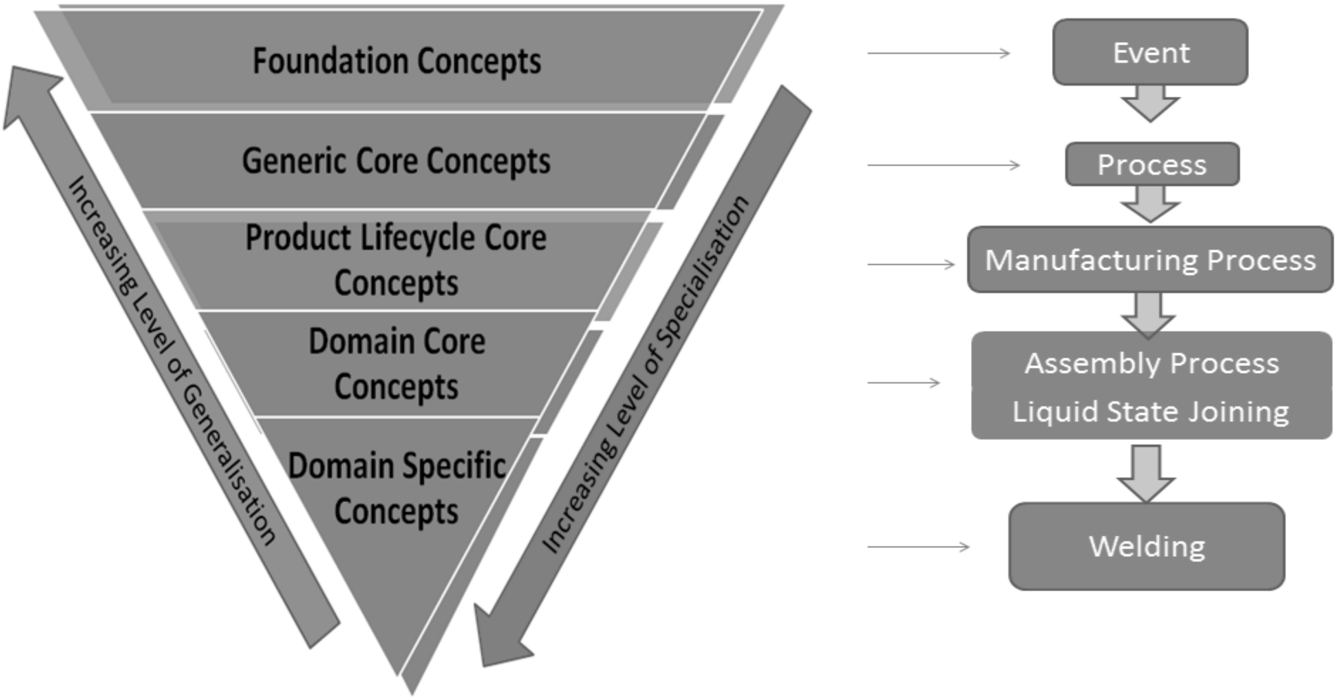


Figure 4: Multiple levels of *Process* concepts

Based on the above concepts, CDOJP is designed and shown in Figure 5. CDOJP is essentially an extension of a more generic Product Lifecycle Ontology (PLO) [40]. The crucial aspects of modelling CDOJP are explained below:

a) The range of key concepts are defined with semantics generic enough to provide a base for any joining process and also specialised enough to provide a direct route for aligning with specific welding standards. For example, in Figure 5, *Assembly Process*, *Liquid State Joining*, are the key concepts identified for joining in order to build up the ontology. The concept of *Welding* is also identified to align the welding standards.

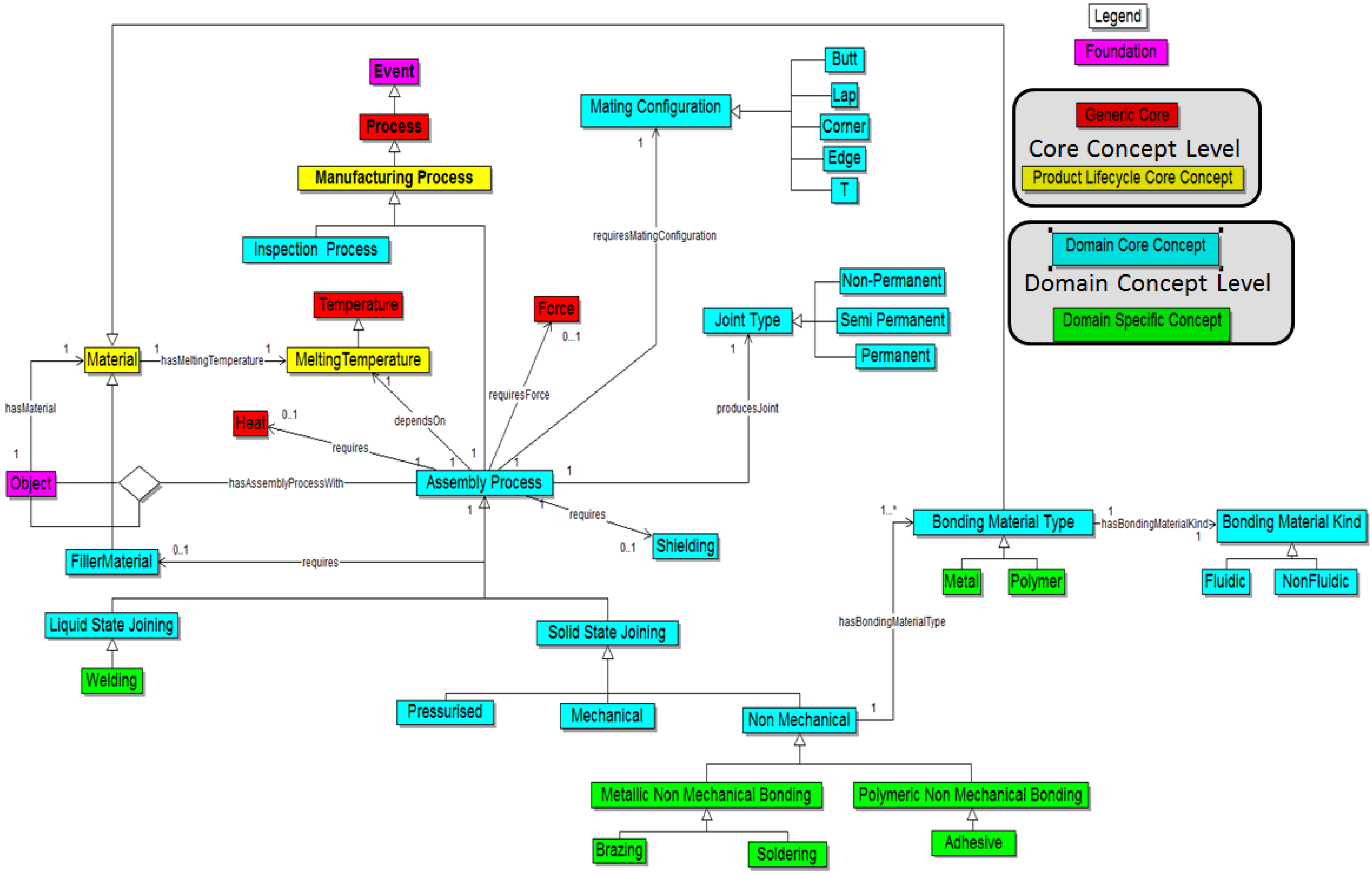


Figure 5: Modelling of CDOJP

b) Based on the key concepts, relationships between them are specified, e.g., the relationship *hasAssemblyProcessWith* is defined between two *Object* using Ternary Operator.

c) The model is devoid of any inconsistencies and incoherencies as it is developed by explicitly defining the semantics of the concept. For example, *Metallic Non Mechanical Bonding Process* and *Polymeric Non Mechanical Bonding Process* are defined as two different sub processes of *Non Mechanical Bonding Process*. This ensures the consistent capture and categorisation of non-mechanical bonding processes with subtle semantic differences.

A more detailed description of modelling the ontology is elaborated in the following sub-sections.

3.2 Modelling Process of CDOJP

There are various ontology development methodologies in literature, such as METHONTOLOGY [41], IDEF-5 methodology [42], CyC [43] and those proposed by [44-46]. However, the methodology proposed by [47] and [31] has been found to be most relevant within the domain of manufacturing [19]. Hence, their methodology with few other additions has been used in this research for development of CDOJP. The additional steps involved are the formal declaration of the concepts along with the testing of their semantics. The problem apprehension for the development has been carried out through literature survey and an industrial case study at an aero engine manufacturing company.

The modelling of CDOJP has been shown in Figure 5, which is based on an UML modelling process in the following steps:

1. The identified core concepts are modelled as classes in a hierarchical form using a top down approach, e.g., the *Manufacturing Process* class which is a top level class was modelled first followed by its more specific *Assembly Process* class.
2. The attributes of the classes are defined through relationships, e.g., the attribute of the *Assembly Process* that it requires *Force* is defined through the relation *requiresForce*.
3. The cardinality of every relationship is defined to capture the uniqueness of the relationships, e.g., 1 to 0.1 cardinality defined for *requiresForce* relationship, signifies that every *Assembly Process* class can have a maximum of one unique relation with the *Force* class.

The CDOJP is then formalised using the Web Ontology Language (OWL) by assigning rules and axioms as elaborated in Section 4. OWL was developed by the World Wide Web Consortium (W3C) [39] and has the capability to process the content of the information rather than just presenting the information, as it provides additional vocabulary with formal semantics [48]. The utilisation of CDOJP to consolidate the standards is one of the verification methods used for demonstrating the semantic capture of the concepts.

3.3 Classes of Concepts

The explicit definitions of the proposed core and the domain concepts are discussed here. It is a crucial step for modelling the ontology. The definitions and the meanings of the terms related to joining and welding found in the literature along with the widely accepted standards have been studied. Some of the definitions have been adopted from the published literature and the standards while the others have been newly proposed. The prefix for each of the concepts denotes the specialisation level that it belongs to and its specificity. The essential classes are described here with their definitions provided in Table 3.

Table 3: Definitions of classes

ProductLifecycleCore:Manufacturing Process *“Structured set of activities or operations that is performed upon an object and contributes towards converting it from a raw material or a semi-finished state to a state of further completion.”*
DomainCoreGeneric:AssemblyProcess *“Process by which a group of components are brought together under specific mating configuration to form a unit.”*
DomainCoreGeneric:LiquidStateJoining *“Process that categorises all the joining processes in which the participating component(s)/substrate material passes through the liquid state before forming the joint”*
DomainCoreGeneric:SolidStateJoining *“ Process categorises all the joining processes in which the participating component(s)/substrate material remains in the solid state throughout the process of forming the joint”*
DomainCoreGeneric:NonMechanicalBondingProcess *“Solid State Joining Process where the bond or the joint between the mating objects interface are produced by a fluidic substance. The fluidic substance acts as the “bonding element or material”.*
DomainCoreGeneric:MechanicalBondingProcess *“Solid State Processes where the bond or the joint between the mating objects interface are produced by a Non-Fluidic or Solid Material such as a Fastener which is used for joining securely and temporarily”*

The *ProductLifecycleCore:ManufacturingProcess* class is a generic concept for the entire product lifecycle including design and manufacturing. *DomainCoreGeneric:AssemblyProcess* class is a specialisation of this class. It includes all those processes in which two or more components are joined together through some form of Bond. Depending on the type of the Bond there can be different *Joint Types*. These are *Permanent Joints, Non-Permanent Joints* & *Semi-Permanent Joints* and are based on the condition of the mating component on bond removal. The *CoreDomainGeneric:MatingConfiguration* class describes the orientation in which every joint is aligned. The different configurations in which they are sub classified are *Butt, Lap, Corner, Edge and T.*

The key factor which differentiates the processes was found to be the joint type as well as the fundamental process by which the bond is created. The key differentiating criteria is the procedure by which the bonding takes place. It also depends on the state of mating component material which can either be liquid or solid. This can be conceived as the primary basis for the classification of the *Assembly Processes* and thus on a holistic level they are classified as DomainCoreGeneric:*LiquidStateJoining* and DomainCoreGeneric:*SolidStateJoining* processes.

From the definitions in Table 3, *LiquidStateJoining* process was found to be the most relevant category for subsuming *DomainCoreSpecific:Welding* class. The justification of such a classification can be found in the origins of the word *Welding* which is an “Alteration of ‘well’ and in the obsolete sense means ‘melt or weld’ heated metal (late 16th century).” [49]. Agreeing on the origins it could be understood that the welding essentially refers to processes where there is an involvement of actual melting of the metal. Fundamentally this means that mating components partly go through the liquid state during the joint forming process. Hence, accordingly *Welding* process should encompass all those processes where there is some form of melting of the metal. From this perspective all the fusion processes should be classified as welding processes.

SolidStateJoining is opposite to the *LiquidStateJoining* and has further categorization. It is further categorized as *NonMechanicalBondingProcess,MechanicalBondingProcess* & *PressurisedBondingProcess.* DomainCoreGeneric:*NonMechanicalBondingProcess* is broadly classified as *DomainCoreSpecific:MetallicNonMetallicBondingProcess* & *DomainCoreSpecific:PolymericBondingProcess.* The differentiating attribute for the two classes of processes lies on the nature of the fluidic material that is used for bonding which can either be *Metal* or *Polymer*. The proper definition of the concepts is an essential step to capture their semantics and further highlight the additional requirements for formalisation. The inter class relationships are also revealed through their proper description.

3.4 Relationships between Classes

From the UML model in Figure 5, it can be observed that all the relationships are defined at a generic level for the super classes. This is based on the understanding that the sub classes inherit all the attributes of their super classes which includes all of their relationships. The prefix of the relationships denotes the specialisation level they exist in and further their dominion. For example, the prefix *CoreDomain* denotes that the concerned relation is between the core domain concepts while *Multi* defines inter-level relationships. Within the hierarchical model the primary relationships originate at *Assembly Process* class. Different cardinality has been assigned for the relationships depending on their constraining requirements. The model in Figure 5 describes at a generic level the concepts and the complex relationships between them. The different relations along with the corresponding classes they connect are shown in Table 4. These are required to describe an assembly process as well as its further categorisation.

Table 4: Relations and classes they connect

Relations/Properties	**Domain**	**Range**
CoreDomain:requiresMatingConfiguration	*AssemblyProcess*	*MatingConfiguration*
CoreDomain:producesJoint	*AssemblyProcess*	*Join Type*
CoreDomain:requiresShielding	*AssemblyProcess*	*Shielding*
CoreDomain:hasBondingMaterialType	*NonMechanicalBonding*	*BondingMaterialType*
Multi:requiresForce	*AssemblyProcess*	*Force*
Multi:requiresHeat	*AssemblyProcess*	*Heat*
Multi:dependsOn	*AssemblyProcess*	*MeltingTemperature*
CoreDomain:requiresFillerMaterial	*AssemblyProcess*	*FillerMaterial*
CoreDomain:hasBondingMaterialType	*BondingMaterialType*	*BondingMaterialKind*

4. Consolidation of CDOJP for Welding Standards

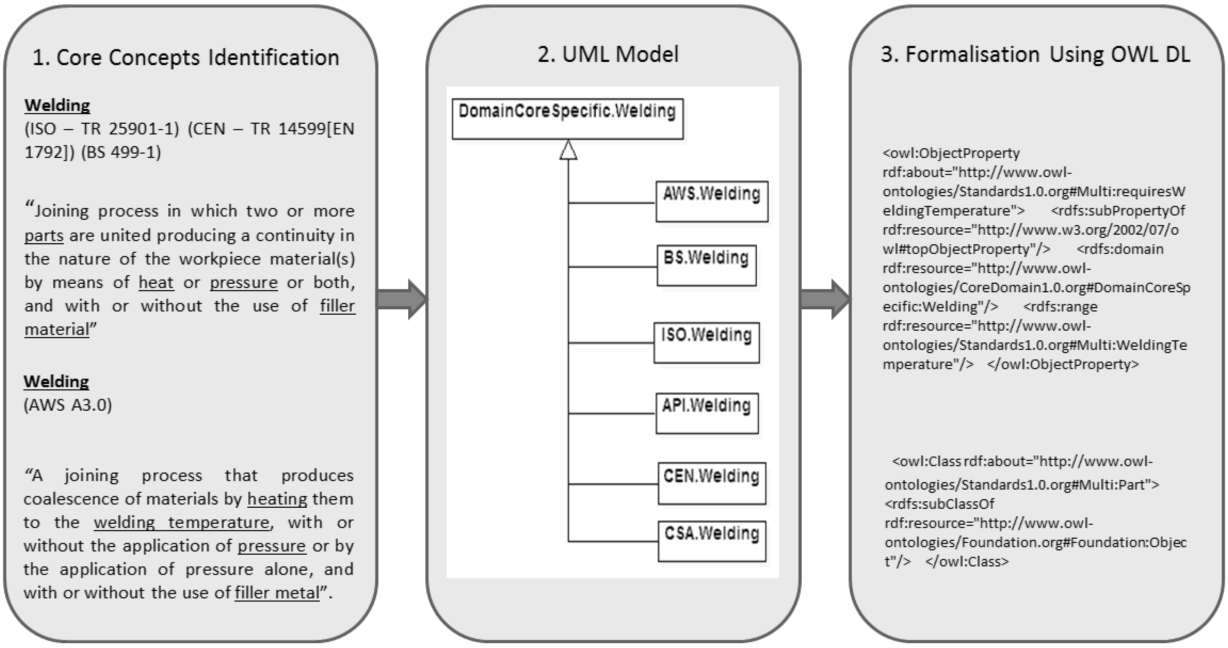
The experiments to verify the semantic capture of the concepts and consistency of the CDOJP is described here. Further, the use of the CDOJP to consolidate the welding standards is also described.

4.1 Implementation of the Proposed Framework

The proposed ontology (CDOJP) is used as a base for consolidation of the welding standards. The concept *Welding* is used to explain the implementation of the proposed framework for the consolidation. Figure 6 shows the implementation of the framework for exploiting OWL DL formalisms in order to consolidate the welding standards.

The first step in the implementation of the framework is to identify the core concepts from the natural language definition of the concepts. The requirement of this step is achieved through a survey of all the welding standards. The compilation of similar terms and their informal definitions revealed the important key words and their respective sentences where they are used. The term *Welding* was found to be referenced across multiple standards. Hence, it is used as a core concept to which the definitions from different standards are tailored. This step also involved a crucial input from the domain expert from the industry as it helped in identifying the other important concepts which are cross referenced across different definitions.

Based on the identified core concepts and their relationship, UML model-CDOJP is constructed. The keywords highlighted within the textual definitions in this step identify the key set of concepts along with their relationships in the CDOJP model. In the final step, the model is formalised into an consolidated ontology using the description logic based language OWL DL.



Welding
(ISO – TR 25901-1) (CEN – TR 14599[EN 1792]) (BS 499-1)

"Joining process in which two or more parts are united producing a continuity in the nature of the workpiece material(s) by means of heat or pressure or both, and with or without the use of filler material"

Welding
(AWS A3.0)

"A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal".

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rdf:resource="http://www.owl-
ontologies/CoreDomain1.0.org#DomainCoreSp
ecific:Welding"/>      <rdfs:range
rdf:resource="http://www.owl-
ontologies/Standards1.0.org#Multi:WeldingTe
mperature"/>   </owl:ObjectProperty>

  <owl:Class rdf:about="http://www.owl-
ontologies/Standards1.0.org#Multi:Part">
<rdfs:subClassOf
rdf:resource="http://www.owl-
ontologies/Foundation.org#Foundation:Objec
t"/>   </owl:Class>
```

Figure 6: Implementation of the framework

4.2 Modelling of CDOJP to Consolidate Welding Standards

The UML model that consolidates the welding standards from CDOJP is elucidated in Figure 7.

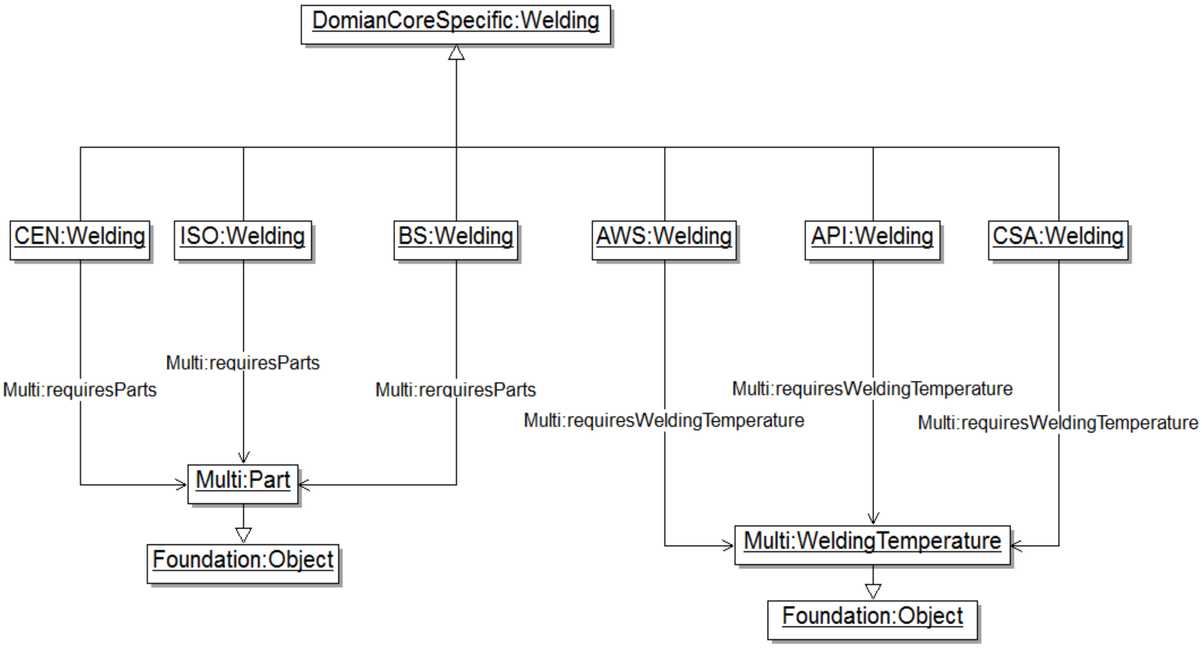


Figure 7: Ontology model for consolidation of welding standards

It portrays the utilisation of the core concept *DomainCoreSpecific:Welding* as a base that provides an avenue to consolidate the welding standards. The entities are captured in the form of classes and relationships. The core concept *DomainCoreSpecific:Welding* has been defined at the generic level to provide the very basic level of semantics to consolidate the welding standards. A specialised relation *Core:requiresMaterial* has been defined for the *Welding* class as this is a specific requirement for this concept. The definitions of welding found in different standards are denoted as specialised classes such as *AWS:Welding, ISO:Welding* etc. These definitions are tailored to the core concept *DomainCoreSpecific:Welding* through the subsumption relation. *Multi:requiresParts* and *Multi:requiresWeldingTemperature* are the two relationships which are defined specifically for capturing the semantics of the definitions found in the two set of standards.

4.3 Formalisation of CDOJP to Consolidate Welding Standards

The penultimate step in the implementation of the entire framework is the consolidation of the ontology. CDOJP is used as a basis for developing the formal model using the OWL DL. OWL is an extension of Resource Description Framework (RDF) and Resource Description Framework Scheme (RDFS) which provides semantics with regards to explicitly representing complex constraints. It uses the syntax of Extensible Markup Language (XML) and RDF [50]. They provide the required syntax and semantics which are required for knowledge modelling within a domain. These are primarily in the form of concepts, relations between the concepts and the logical constraints which they satisfy. In the following, the consolidation of CDOJP will follows the fundamental elements for modelling in OWL, i.e.,

1. Namespaces
2. Classes (Concepts) and Relations (Properties)
3. Restrictions

Namespace Declaration

In OWL DL, namespaces act as identifiers to represent the ontological entities and further address the different contexts. They provide overall indications regarding the background of the vocabularies used. The following declaration shows the method of declaring the 'Core' identifier for the proposed ontology.

```
xmlns="http://www.owl-ontologies/CoreDomain.org#"
xml:base=http://www.owl-ontologies/CoreDomain.org
```

Classes & Relation Declaration

The concepts are declared in OWL DL in the form of classes while relations are declared as properties. The concept *AssemblyProcess* as well as *Welding* has been used to describe the methodology of declaring classes and relations. Both of the classes belong to the 'CoreDomain' namespace. The 'CoreDomain' ontology imports the more generic 'ProductLifecycleCore' ontology as *AssemblyProcess* is a specialisation of the generic class *ManufacturingProcess*. The import function is implemented using the following syntax.

```
<owl:Ontologyrdf:about="http://www.owl-ontologies/CoreDomain.org">
<owl:importsrdf:resource="http://www.owl-ontologies/ProductLifecycleCore.org"/>
</owl:Ontology>
```

The rdfs:subClassOf directive is used to capture the subsumption relations. The following syntax asserts DomainCoreSpecific:Welding class as a sub-class of *DomainCoreGeneric:LiquidStateJoining*.

```
<owl:Classrdf:about="http://www.owl-ontologies/CoreDomain.org#DomainCoreSpecific:Welding">
<rdfs:subClassOf rdf:resource="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:LiquidStateJoining"/>
</owl:Class>
```

The binary relations in OWL DL is declared using the owl:ObjectProperty directive. The directionality of the relationships are specified by their domain (rdfs:domain) and range (rdfs:range) respectively. The declaration of the object property relation *CoreDomain:notReachesMeltingTemperature* is shown below

```
<owl:ObjectProperty rdf:about="http://www.owl-ontologies/CoreDomain.org#CoreDomain:notReachesMeltingTemperature">
<rdfs:domain rdf:resource="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:BaseMaterial"/>
<rdfs:range   rdf:resource="http://www.owl-ontologies/ProductLifecycleCore.org#ProductLifecycleCore:MeltingTemperature"/>
</owl:ObjectProperty>
```

Restrictions in OWL

The restrictions in the OWL DL are for defining the constraints and axioms which infuses semantic enrichment to the ontology. These axioms provide the consistency checking of the ontology which includes the assertion of individuals in to the Knowledge Bases (KB) created in OWL. Further, they also act as inference rules that can infer new knowledge based on the restrictions and identify the equivalency as well as relations among the classes. OWL DL provides two types of restrictions which are 'necessary conditions' and 'necessary & sufficient conditions'.

The 'necessary conditions' are used to support the creation of a primitive class by specifying an anonymous super class of a named class. Figure 8 below depicts the 'necessary conditions' placed on the class *DomainCoreGeneric:LiquidStateJoining*. It ensures the semantic consistency of the instances of the class has a relation with instances of the *ProductLifecycleCore:MeltingTemperature* class through the *CoreDomain:reachesMeltingTemperature* relation. The restrictions further ensure that any defined classes having the above mentioned restrictions would subclassify DomainCoreGeneric:LiquidStateJoining.

```
<owl:Class rdf:about="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:LiquidStateJoining">
    <rdfs:subClassOf rdf:resource="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:AssemblyProcess"/>
    <rdfs:subClassOf>
        <owl:Restriction>
            <owl:onProperty rdf:resource="http://www.owl-ontologies/CoreDomain.org#CoreDomain:reachesMeltingTemperature"/>
            <owl:someValuesFrom rdf:resource="http://www.owl-ontologies/ProductLifecycleCore.org#ProductLifecycleCore:MeltingTemperature"/>
        </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
        <owl:Restriction>
            <owl:onProperty rdf:resource="http://www.owl-ontologies/CoreDomain.org#CoreDomain:requiresFillerMaterial"/>
            <owl:maxQualifiedCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#nonNegativeInteger">1</owl:maxQualifiedCardinality>
            <owl:onClass rdf:resource="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:FillerMaterial"/>
        </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
        <owl:Restriction>
            <owl:onProperty rdf:resource="http://www.owl-ontologies/CoreDomain.org#CoreDomain:requiresShielding"/>
            <owl:maxQualifiedCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#nonNegativeInteger">1</owl:maxQualifiedCardinality>
            <owl:onClass rdf:resource="http://www.owl-ontologies/CoreDomain.org#DomainCoreGeneric:Shielding"/>
        </owl:Restriction>
    </rdfs:subClassOf>
</owl:Class>
```

Figure 8: Implementing ‘Necessary’ conditions

The ‘necessary & sufficient conditions’ are used to support the creation of a defined class by specifying an anonymous super class of a named class. Figure 9 shows use of this type of restrictions for the *ISO:Welding* class. The restriction provides the consistency checking for the instances of *ISO:Welding* class that has to be related to some instances of the *Multi:Part* class through the *Multi:requiresParts* relation. Further it infers that any other class which has similar restrictions is its equivalent class.

```
<owl:Class rdf:about="http://www.owl-ontologies/Standards1.0.org#ISO:Welding">
    <owl:equivalentClass>
        <owl:Class>
            <owl:intersectionOf rdf:parseType="Collection">
                <rdf:Description rdf:about="http://www.owl-ontologies/CoreDomain1.0.org#DomainCoreSpecific:Welding"/>
                <owl:Restriction>
                    <owl:onProperty rdf:resource="http://www.owl-ontologies/Standards1.0.org#Multi:requiresParts"/>
                    <owl:someValuesFrom rdf:resource="http://www.owl-ontologies/Standards1.0.org#Multi:Part"/>
                </owl:Restriction>
            </owl:intersectionOf>
        </owl:Class>
    </owl:equivalentClass>
</owl:Class>
```

Figure 9: Implementing ‘Necessary’ and ‘Sufficient’conditions

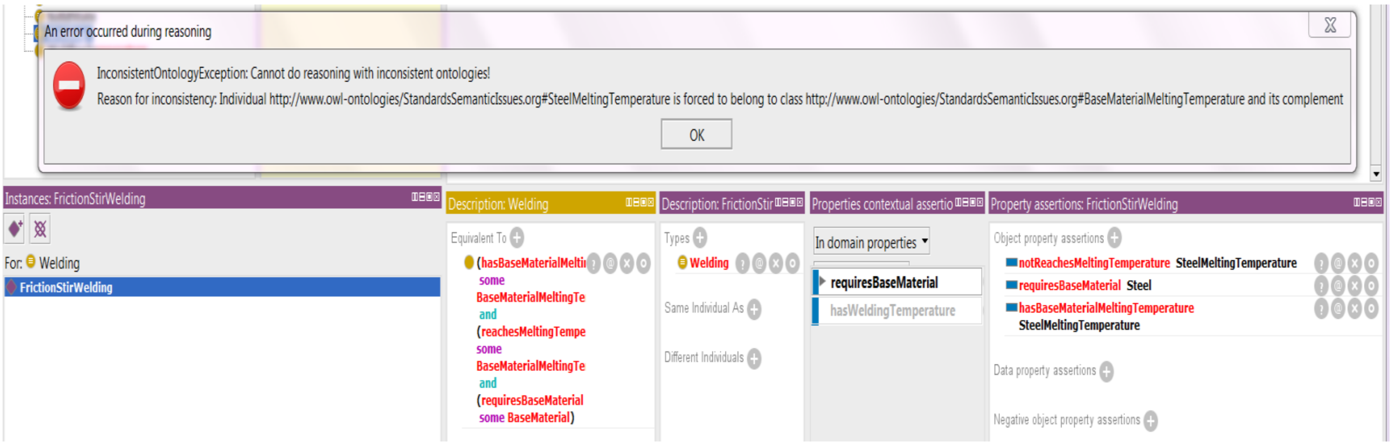
5. Experimental Verification

This research is validated in an industrial environment in collaboration with one of the largest aero engine manufacturing companies. This section describes the various test cases carried out on the ontology to verify the capture of its requirements stated in Sections 2-4. This includes the following:

1. Consistency checking of the formalised ontology,
2. Verification of semantic capture
3. Inference of new taxonomy
4. Consolidation of the welding standards.

The environment of the Protégé – OWL ontology editor is used as the platform for development and deployment of the ontology. The verification of the semantic inconsistencies of welding standards will be described as well.

The semantic issues within and across the standards for ICT systems has been elaborated in Section 2. The limitation of the text based semantics as well as the inconsistency is shown through the formalisation of the *Welding* concept followed by assertion of 'Friction Stir Welding' process. The formalised definition of *Welding* process according to the AWS standard requires *Welding Temperature* to be equal to the base material's *Melting Temperature*. However, the *Friction Stir Welding* process does not involve any melting of the base material implying that the welding temperature is lower than the melting temperature. The standards classify it as a Welding process. Thus, assertion of Friction Stir Process results in inconsistency revealed in Figure 10.



InconsistentOntologyException: Cannot do reasoning with inconsistent ontologies!

Reason for inconsistency: Individual http://www.owl-ontologies/StandardsSemanticIssues.org#SteelMeltingTemperature is forced to belong to class http://www.owl-ontologies/StandardsSemanticIssues.org#BaseMaterialMeltingTemperature and its complement

(hasBaseMaterialMelti some BaseMaterialMeltingTe and (reachesMeltingTempe some BaseMaterialMeltingTe and (requiresBaseMaterial some BaseMaterial)

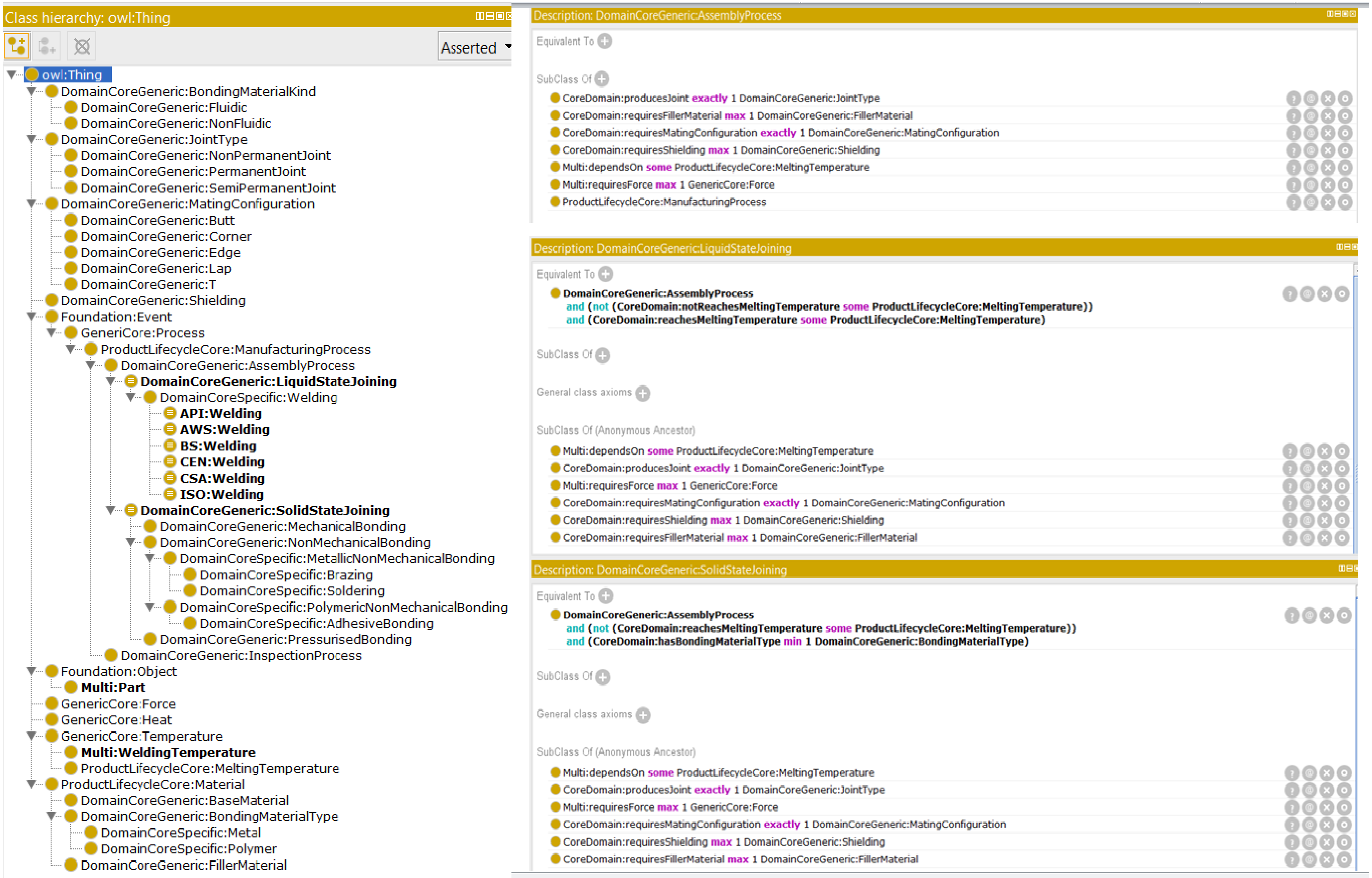
notReachesMeltingTemperature SteelMeltingTemperature
requiresBaseMaterial Steel
hasBaseMaterialMeltingTemperature SteelMeltingTemperature

Figure 10: Inconsistency in welding standards

The complete taxonomy of all the concepts starting from the foundation level to the specific domain of Welding is illustrated in Figure 11. The classes belonging to each specialisation level has been imported from its predecessor. The capture of the 'necessary conditions' for the *DomainCoreGeneric:AssemblyProcess* shown in Figure 11 is through the properties defined within 'SubClass Of' category. These semantics are reused along with several specifics for each specialisation levels and contribute towards distinguished definitions of joining processes. The capture of the 'necessary and sufficient conditions' is revealed in Figure 11 through the 'Equivalent To' category. Figure 12 shows similar inherited as well specific properties assigned for different *Welding* concepts from the standards. These conditional properties expedite consistency checking of the instantiated information. Figure 13 shows assertions of 'Friction Stir Welding' which is an instance of *Welding* class. The missing semantics are marked with red which prompts the user to populate these values. The Pellet reasoner has been used to check the consistency of the ontology which includes assertions of instances. However, the assertion of 'Friction Stir Welding' as an instance of *Welding* class results in error as shown in Figure 14 (a) with its explanation revealed in Figure 14 (b) . This is due to the inherent semantics of the class defined through the assigned properties. This verifies the capture of semantics of the proposed model and the corresponding definitions of the concepts.

Apart from consistency checking, the restrictions further allow inference of new knowledge. The inferences are normally deductive, inductive, abductive or analogical [51]. The inferred hierarchy of the classes as shown in Figure 15 was obtained after the Pellet reasoner was deployed. This enables in identifying the commonalities between the different *Welding* classes as it reveals their subsumptions and equivalency. Based on the various OWL restrictions implemented on the *Welding* class, the reasoner is able to identify the equivalency between two groups of classes as shown in Figure 15. One of the group comprised of *AWS:Welding, CSA:Welding* and *API:Welding* classes while other group was that of *ISO:Welding, CEN:Welding* and *BS:Welding*. This verifies that the proposed model is able to consolidate the welding standards through the definition of welding as stated in different standards. Therefore, CDOJP is verified to provide tailored semantics for welding standards that remove the highlighted issues, connects them, makes them consistent and provides a base for interoperability across them.

The extent of interoperability achieved by the proposed model through rigorously defined semantics is further validated by using Semantic Web Rule Language (SWRL). It is an extension of OWL that permits complex rule definitions and advance reasoning over the concepts. These rules help the system to interpret and infer the processes which are similar but have been differentially termed across the standards. An example of this shown in Figure 16, where (a) shows the SWRL rule used for make the system identify that 'Gas Tungsten Arc Welding(GTAW)' mentioned in the AWS standard is same as 'Tungsten Inert Gas (TIG)' of ISO standards(Figure 16 (b)). Figure 16 (c) shows the Semantic Query-Enhanced Web Rule Language (SQWRL) query that is used to enquire the knowledge base for displaying the particular set of results.



- owl:Thing
  - DomainCoreGeneric:BondingMaterialKind
    - DomainCoreGeneric:Fluidic
    - DomainCoreGeneric:NonFluidic
  - DomainCoreGeneric:JointType
    - DomainCoreGeneric:NonPermanentJoint
    - DomainCoreGeneric:PermanentJoint
    - DomainCoreGeneric:SemiPermanentJoint
  - DomainCoreGeneric:MatingConfiguration
    - DomainCoreGeneric:Butt
    - DomainCoreGeneric:Corner
    - DomainCoreGeneric:Edge
    - DomainCoreGeneric:Lap
    - DomainCoreGeneric:T
  - DomainCoreGeneric:Shielding
  - Foundation:Event
    - GeneriCore:Process
      - ProductLifecycleCore:ManufacturingProcess
        - DomainCoreGeneric:AssemblyProcess
          - **DomainCoreGeneric:LiquidStateJoining**
            - DomainCoreSpecific:Welding
              - **API:Welding**
              - **AWS:Welding**
              - **BS:Welding**
              - **CEN:Welding**
              - **CSA:Welding**
              - **ISO:Welding**
          - **DomainCoreGeneric:SolidStateJoining**
            - DomainCoreGeneric:MechanicalBonding
            - DomainCoreGeneric:NonMechanicalBonding
              - DomainCoreSpecific:MetallicNonMechanicalBonding
                - DomainCoreSpecific:Brazing
                - DomainCoreSpecific:Soldering
              - DomainCoreSpecific:PolymericNonMechanicalBonding
                - DomainCoreSpecific:AdhesiveBonding
            - DomainCoreGeneric:PressurisedBonding
        - DomainCoreGeneric:InspectionProcess
  - Foundation:Object
    - **Multi:Part**
  - GenericCore:Force
  - GenericCore:Heat
  - GenericCore:Temperature
    - **Multi:WeldingTemperature**
    - ProductLifecycleCore:MeltingTemperature
  - ProductLifecycleCore:Material
    - DomainCoreGeneric:BaseMaterial
    - DomainCoreGeneric:BondingMaterialType
      - DomainCoreSpecific:Metal
      - DomainCoreSpecific:Polymer
    - DomainCoreGeneric:FillerMaterial

Description: DomainCoreGeneric:AssemblyProcess

Equivalent To

SubClass Of

- CoreDomain:producesJoint **exactly** 1 DomainCoreGeneric:JointType
- CoreDomain:requiresFillerMaterial **max** 1 DomainCoreGeneric:FillerMaterial
- CoreDomain:requiresMatingConfiguration **exactly** 1 DomainCoreGeneric:MatingConfiguration
- CoreDomain:requiresShielding **max** 1 DomainCoreGeneric:Shielding
- Multi:dependsOn **some** ProductLifecycleCore:MeltingTemperature
- Multi:requiresForce **max** 1 GenericCore:Force
- ProductLifecycleCore:ManufacturingProcess

Description: DomainCoreGeneric:LiquidStateJoining

Equivalent To

- **DomainCoreGeneric:AssemblyProcess**
  and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
  and (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature)

SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

- Multi:dependsOn **some** ProductLifecycleCore:MeltingTemperature
- CoreDomain:producesJoint **exactly** 1 DomainCoreGeneric:JointType
- Multi:requiresForce **max** 1 GenericCore:Force
- CoreDomain:requiresMatingConfiguration **exactly** 1 DomainCoreGeneric:MatingConfiguration
- CoreDomain:requiresShielding **max** 1 DomainCoreGeneric:Shielding
- CoreDomain:requiresFillerMaterial **max** 1 DomainCoreGeneric:FillerMaterial

Description: DomainCoreGeneric:SolidStateJoining

Equivalent To

- **DomainCoreGeneric:AssemblyProcess**
  and (not (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
  and (CoreDomain:hasBondingMaterialType min 1 DomainCoreGeneric:BondingMaterialType)

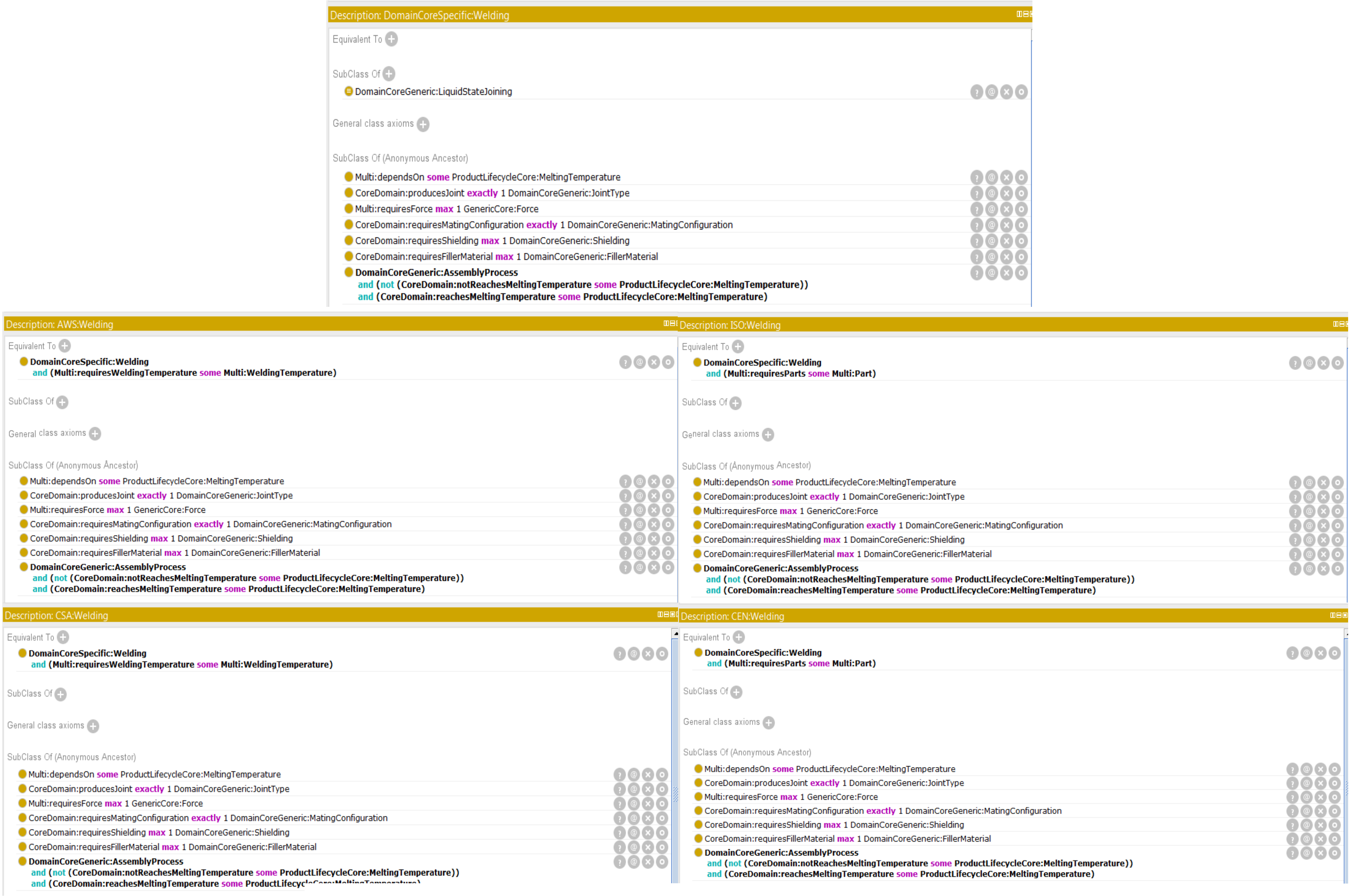
SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

- Multi:dependsOn **some** ProductLifecycleCore:MeltingTemperature
- CoreDomain:producesJoint **exactly** 1 DomainCoreGeneric:JointType
- Multi:requiresForce **max** 1 GenericCore:Force
- CoreDomain:requiresMatingConfiguration **exactly** 1 DomainCoreGeneric:MatingConfiguration
- CoreDomain:requiresShielding **max** 1 DomainCoreGeneric:Shielding
- CoreDomain:requiresFillerMaterial **max** 1 DomainCoreGeneric:FillerMaterial

Figure 11: Taxonomy & relations of all concepts



Description: DomainCoreSpecific:Welding

Equivalent To

SubClass Of

DomainCoreGeneric:LiquidStateJoining

General class axioms

SubClass Of (Anonymous Ancestor)

Multi:dependsOn some ProductLifecycleCore:MeltingTemperature
CoreDomain:producesJoint exactly 1 DomainCoreGeneric:JointType
Multi:requiresForce max 1 GenericCore:Force
CoreDomain:requiresMatingConfiguration exactly 1 DomainCoreGeneric:MatingConfiguration
CoreDomain:requiresShielding max 1 DomainCoreGeneric:Shielding
CoreDomain:requiresFillerMaterial max 1 DomainCoreGeneric:FillerMaterial
DomainCoreGeneric:AssemblyProcess
and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
and (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature)

Description: AWS:Welding

Equivalent To

DomainCoreSpecific:Welding
and (Multi:requiresWeldingTemperature some Multi:WeldingTemperature)

SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

Multi:dependsOn some ProductLifecycleCore:MeltingTemperature
CoreDomain:producesJoint exactly 1 DomainCoreGeneric:JointType
Multi:requiresForce max 1 GenericCore:Force
CoreDomain:requiresMatingConfiguration exactly 1 DomainCoreGeneric:MatingConfiguration
CoreDomain:requiresShielding max 1 DomainCoreGeneric:Shielding
CoreDomain:requiresFillerMaterial max 1 DomainCoreGeneric:FillerMaterial
DomainCoreGeneric:AssemblyProcess
and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
and (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature)

Description: ISO:Welding

Equivalent To

DomainCoreSpecific:Welding
and (Multi:requiresParts some Multi:Part)

SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

Multi:dependsOn some ProductLifecycleCore:MeltingTemperature
CoreDomain:producesJoint exactly 1 DomainCoreGeneric:JointType
Multi:requiresForce max 1 GenericCore:Force
CoreDomain:requiresMatingConfiguration exactly 1 DomainCoreGeneric:MatingConfiguration
CoreDomain:requiresShielding max 1 DomainCoreGeneric:Shielding
CoreDomain:requiresFillerMaterial max 1 DomainCoreGeneric:FillerMaterial
DomainCoreGeneric:AssemblyProcess
and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
and (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature)

Description: CSA:Welding

Equivalent To

DomainCoreSpecific:Welding
and (Multi:requiresWeldingTemperature some Multi:WeldingTemperature)

SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

Multi:dependsOn some ProductLifecycleCore:MeltingTemperature
CoreDomain:producesJoint exactly 1 DomainCoreGeneric:JointType
Multi:requiresForce max 1 GenericCore:Force
CoreDomain:requiresMatingConfiguration exactly 1 DomainCoreGeneric:MatingConfiguration
CoreDomain:requiresShielding max 1 DomainCoreGeneric:Shielding
CoreDomain:requiresFillerMaterial max 1 DomainCoreGeneric:FillerMaterial
DomainCoreGeneric:AssemblyProcess
and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
and (CoreDomain:reachesMeltingTemperature some ProductLifecyc

Description: CEN:Welding

Equivalent To

DomainCoreSpecific:Welding
and (Multi:requiresParts some Multi:Part)

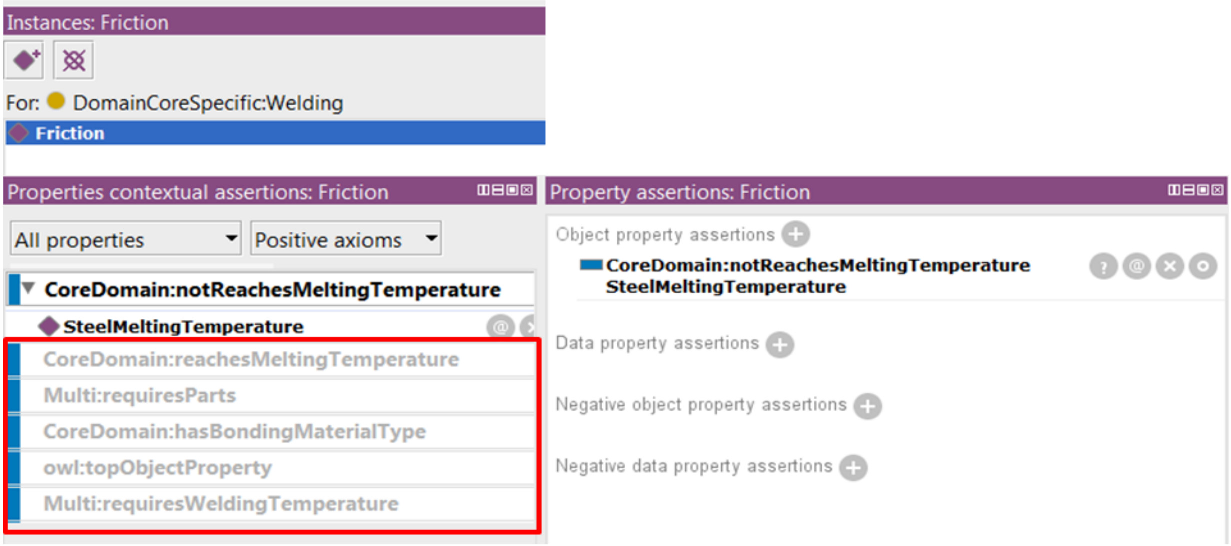
SubClass Of

General class axioms

SubClass Of (Anonymous Ancestor)

Multi:dependsOn some ProductLifecycleCore:MeltingTemperature
CoreDomain:producesJoint exactly 1 DomainCoreGeneric:JointType
Multi:requiresForce max 1 GenericCore:Force
CoreDomain:requiresMatingConfiguration exactly 1 DomainCoreGeneric:MatingConfiguration
CoreDomain:requiresShielding max 1 DomainCoreGeneric:Shielding
CoreDomain:requiresFillerMaterial max 1 DomainCoreGeneric:FillerMaterial
DomainCoreGeneric:AssemblyProcess
and (not (CoreDomain:notReachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature))
and (CoreDomain:reachesMeltingTemperature some ProductLifecycleCore:MeltingTemperature)

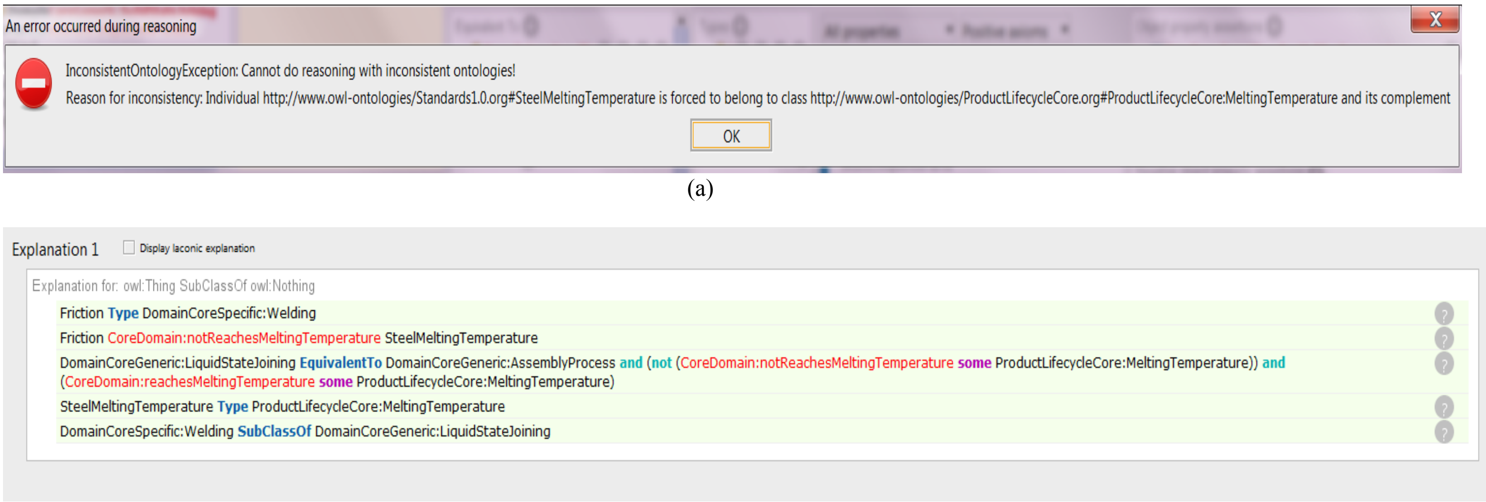
Figure 12: Properties assigned to welding classes



CoreDomain:notReachesMeltingTemperature
SteelMeltingTemperature
CoreDomain:reachesMeltingTemperature
Multi:requiresParts
CoreDomain:hasBondingMaterialType
owl:topObjectProperty
Multi:requiresWeldingTemperature

CoreDomain:notReachesMeltingTemperature SteelMeltingTemperature

Figure 13: Instance assertion with missing semantics



InconsistentOntologyException: Cannot do reasoning with inconsistent ontologies!
Reason for inconsistency: Individual http://www.owl-ontologies/Standards1.0.org#SteelMeltingTemperature is forced to belong to class http://www.owl-ontologies/ProductLifecycleCore.org#ProductLifecycleCore:MeltingTemperature and its complement

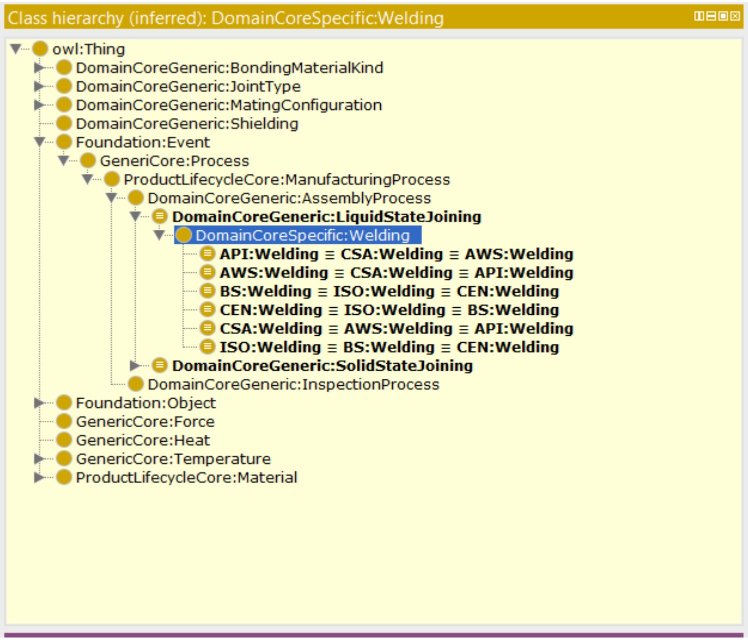
(a)

Explanation for: owl:Thing SubClassOf owl:Nothing

Friction **Type** DomainCoreSpecific:Welding
Friction CoreDomain:notReachesMeltingTemperature SteelMeltingTemperature
DomainCoreGeneric:LiquidStateJoining **EquivalentTo** DomainCoreGeneric:AssemblyProcess **and** (**not** (CoreDomain:notReachesMeltingTemperature **some** ProductLifecycleCore:MeltingTemperature)) **and** (CoreDomain:reachesMeltingTemperature **some** ProductLifecycleCore:MeltingTemperature)
SteelMeltingTemperature **Type** ProductLifecycleCore:MeltingTemperature
DomainCoreSpecific:Welding **SubClassOf** DomainCoreGeneric:LiquidStateJoining

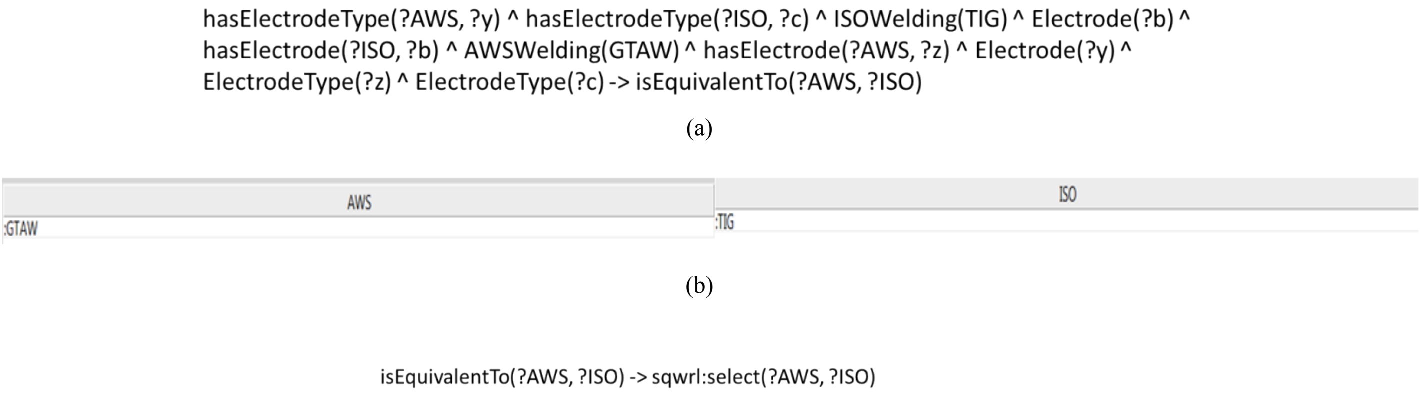
(b)

Figure 14: (a) Error message for incorrect assertion (b) Explanation of inconsistency from the system



owl:Thing
DomainCoreGeneric:BondingMaterialKind
DomainCoreGeneric:JointType
DomainCoreGeneric:MatingConfiguration
DomainCoreGeneric:Shielding
Foundation:Event
GeneriCore:Process
ProductLifecycleCore:ManufacturingProcess
DomainCoreGeneric:AssemblyProcess
DomainCoreGeneric:LiquidStateJoining
DomainCoreSpecific:Welding
API:Welding ≡ CSA:Welding ≡ AWS:Welding
AWS:Welding ≡ CSA:Welding ≡ API:Welding
BS:Welding ≡ ISO:Welding ≡ CEN:Welding
CEN:Welding ≡ ISO:Welding ≡ BS:Welding
CSA:Welding ≡ AWS:Welding ≡ API:Welding
ISO:Welding ≡ BS:Welding ≡ CEN:Welding
DomainCoreGeneric:SolidStateJoining
DomainCoreGeneric:InspectionProcess
Foundation:Object
GenericCore:Force
GenericCore:Heat
GenericCore:Temperature
ProductLifecycleCore:Material

Figure 15: Inferred classes showing equivalencies



```
hasElectrodeType(?AWS, ?y) ^ hasElectrodeType(?ISO, ?c) ^ ISOWelding(TIG) ^ Electrode(?b) ^
hasElectrode(?ISO, ?b) ^ AWSWelding(GTAW) ^ hasElectrode(?AWS, ?z) ^ Electrode(?y) ^
ElectrodeType(?z) ^ ElectrodeType(?c) -> isEquivalentTo(?AWS, ?ISO)
```

(a)

AWS	ISO
:GTAW	:TIG

(b)

```
isEquivalentTo(?AWS, ?ISO) -> sqwrl:select(?AWS, ?ISO)
```

(c)

Figure 16 (a) SWRL rule declaration (b) Output revealing same processes with different names in different standards (c) SQWRL query for querying the knowledge base

6. Conclusions

The wide spread innovation in joining sciences has led to the development or a varied range of joining processes. Welding is a type of joining process which has extensive applications and requires regularisation. Various welding standards have been developed for ensuring manufacturing consistency and process control. However, there are several inconsistencies and incoherencies in terms of process categorisation within and across the welding standards. This paper reports investigations into the limitations and issues with welding standards for interoperability and knowledge sharing. Based on the identified limitation of text based semantics of welding concepts, Core Domain Ontology for Joining Processes (CDOJP) is proposed to act as a semantic base that reconciles the semantic inconsistencies and incoherencies prevalent in the standards. It is used to semantically categorise the joining processes, and is further exploited to consolidate the welding standards by formally capturing the tailored text based definitions. The ontological formalisation of the proposed model is carried out using Web Ontology Language (OWL) with industrial validation from one of the largest aero engine manufacturing companies.

This research has contributed by, systematically investigating the semantic inconstancy issues in welding standards, proposing a formal ontology for joining processes, capturing semantics of welding concepts, resolving semantic inconsistencies within and across welding standards and finally facilitating the knowledge sharing across welding domains that use different standards.

The recommendations from this work are planned to be fed into the technical committees overseeing the standards to improve the standards for better interoperability. The standard committee should potentially consider the definition of the core concepts while developing the *Welding* standards as they can be specialised from the core ontology. This model can further be tested for other joining processes and standards for its applicability across entire product lifecycle.

Acknowledgement

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Appendices

Appendix 1: Welding standards referring to ISO/CEN

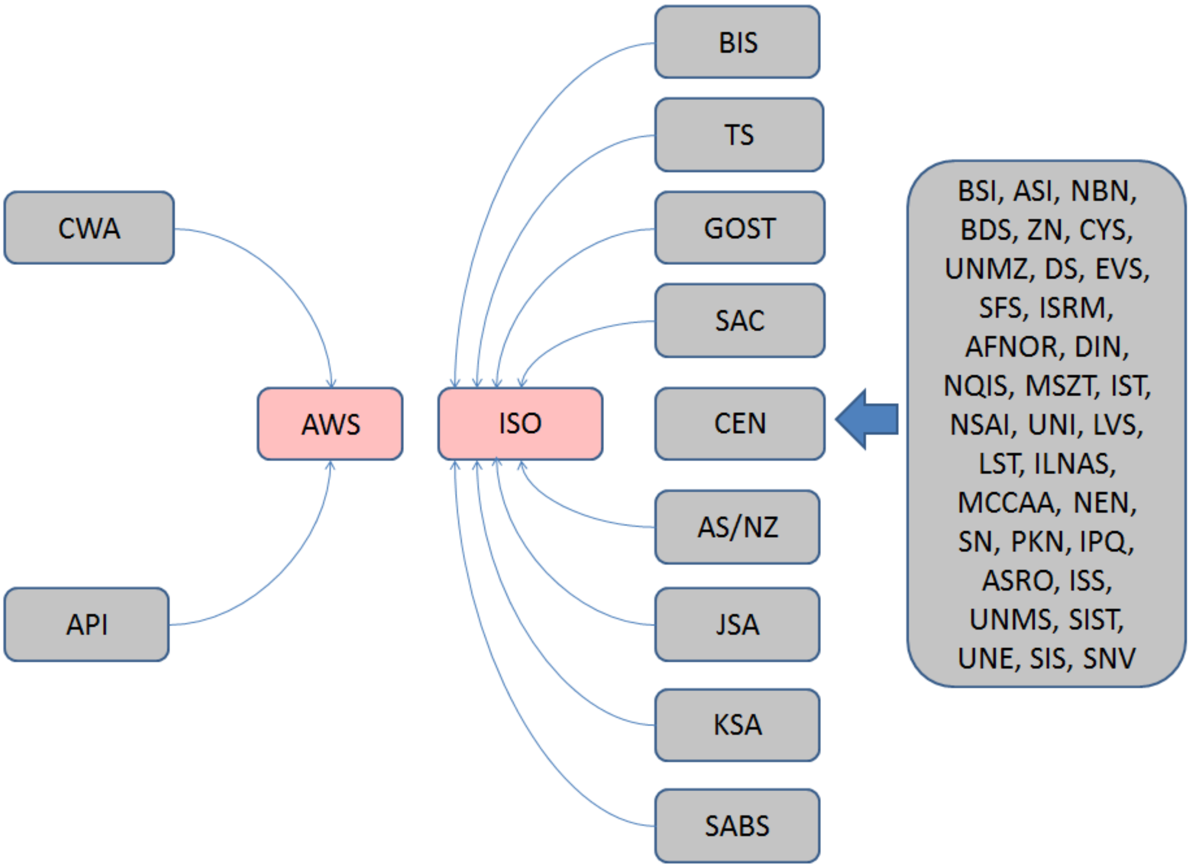
Standard Bodies Referring To ISO/CEN			
Osterreichisches Normungsinstitut - Austrian Standards Institute (ASI)	Austria	TC 037	ONORM EN ISO 4063:2011, ONORM EN 1792:2003
Bureau de Normalisation/Bureau voor Normalisatie (NBN)	Belgium		NBN CEN/TR 14599
Bulgarian Institute for Standardization (BDS)	Bulgaria	TC-30	БДС EN 14610:2009
Croatian Standards Institute (HZN)	Croatia		Refers CEN
Cyprus Organization for Standardisation (CYS)	Cyprus		Refers CEN
Czech Office for Standards, Metrology and Testing (UNMZ)	Czech Republic	70	Refers CEN
Dansk Standard (DS)	Denmark	S-047	DS DS-handbog 106.2
Estonian Centre for Standardisation (EVS)	Estonia		Refers CEN
Finish Standards Association (SFS)	Finland		Refers CEN
Standardization Institute of the Republic of Macedonia (ISRM)	Former Yugoslav Republic of Macedonia	TC 39	МКС EN 14610: 2010
Association Française de Normalisation (AFNOR)	France		FD ISO/TR 25901-3:2017,
Deutsches Institut für Normung (DIN)	Germany		DIN 1910-100 (2008-02), DIN EN ISO 4063 (2011-03),
National Quality Infrastructure System (NQIS/ELOT)	Greece		Refers to CEN
Hungarian Standards Institution (MSZT)	Hungary		Refers to CEN
Icelandic Standards (IST)	Iceland		Refers to CEN
National Standards Authority of	Ireland		I.S. EN ISO 4063:2010, I.S.

Ireland (NSAI)			CEN/TR 14599:2005, I.S. EN ISO 17659:2004
Ente Nazionale Italiano di Unificazione (UNI)	Italy		UNI CEN/TR 14599:2012, UNI EN ISO 17659:2006
Latvian Standard Ltd. (LVS)	Latvia		Refers to CEN
Lithuanian Standards Board (LST)	Lithuania	TK 41	LST CEN / TR 14599: 2013
Organisme Luxembourgeois de Normalisation (ILNAS)	Luxembourg		Refers to CEN
The Malta Competition and Consumer Affairs Authority (MCCAA)	Malta		Refers to CEN
Nederlands Normalisatie-instituut (NEN)	Netherlands		NEN NPR ISO/TR 25901-3:2016, NEN NPR ISO/TR 25901-4:2016, NEN NPR ISO/TR 25901-1:2016
Norges Standardiseringsforbund Standards Norway (SN)	Norway		NS EN ISO 4063:2010, NS EN 1792
Polish Committee for Standardization (PKN)	Poland	TC 165	PN EN 1792:2010, PN EN ISO 17659:2008, PN EN 14610:2008
Instituto Português da Qualidade (IPQ)	Portugal	CT 019	Refers to CEN
Romanian Standards Association (ASRO)	Romania	CT 39	Refers to CEN
Institute for Standardization of Serbia (ISS)	Serbia	M044	SRPS CEN/TR 14599:2009
Slovak Office of Standards Metrology and Testing (UNMS)	Slovakia		Refers to CEN
Slovenian Institute for Standardization (SIST)	Slovenia	TRM	Refers to CEN
Asociación Española de Normalización (UNE)	Spain	CTN 14	UNE CEN/TR 14599:2006, UNE EN ISO 17659:2005, UNE EN ISO 4063:2010, UNE EN 14610:2006
Standardiserings-Kommissionen I Sverige - Swedish Standards Institute (SIS)	Sweden	TK 134	SS EN ISO 4063 Ed. 3 (2010), SS EN 14610 Ed. 1 (2005), SS EN ISO 17659 Ed. 1 (2005)
Schweizerische Normen-Vereinigung (SNV)	Switzerland		SNV DIN 8528-1:1973, SN EN ISO 4063:2011, SN EN ISO 17659:2004
Turkish Standards Institution (TSE)	Turkey		TSE TS 6261
Standards Australia & Standards New Zealand (AS/NZ)	Australia & New Zealand	WD-001	AS 2812-2005
Gosudarstvennyy standart) (GOST):Euro-Asian Council for Standardization, Metrology & Certification (EASC)	Russia, Belarus, Moldova, Kazakhstan, Azerbaijan, Armenia, Kyrgyzstan, Uzbekistan, Tajikistan, Georgia, Turkmenistan	EASC	GOST R ИСО 857-1-2009, GOST R ИСО 17659-2009,
Japanese Standards Association (JSA): Japanese Industrial Standards (JIS)	Japan		JIS Z 3000-1,JIS Z 3000-2,JIS Z 3000-3, JIS Z 3000-4, JIS Z 3000-6
Korean Standards Association (KSA)	Korea		KS B ISO 857-2:2013

South African Bureau of Standards (SABS)	South Africa	44	SANS 10044-1 Ed. 3 (2004/R2011), SANS 4063 Ed. 3 (2011),
Standardization Administration of the People's Republic of China (SAC)	People's Republic of China		SAC GB/T 3375-94

Appendix 2: Welding standards referring to AWS

Standard Bodies Referring To AWS		
Canadian Welding Association (CWA): Canadian Welding Bureau (CWB)	Canada	
American Petroleum Institute (API)	America	



Appendix 3: Map of welding standards