dstv: An ontology-based extension of the DSTV-NC standard for the use of linked data in the automation of steel construction

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Abstract

To meet the demands of automated steel construction, there is a need for innovative ways to link process data, measured deviations, and tolerances. Our current research in robotic steel fabrication aims to tackle this challenge by creating an adaptable information model interface that can seamlessly incorporate cross-process considerations required for precise and efficient fabrication beyond current Building Information Modeling (BIM). The goal is to improve existing information interfaces and increase the utilization of flexible and partially automated robot concepts in steel construction. Our approach uses existing standards and product interfaces such as DSTV-NC in steel construction, which we convert and enhance through an ontology that includes tolerances and process parameters. The outcomes of our study contribute to the development of automated systems in construction and support small and medium-sized enterprises in steel construction by addressing challenges related to skills shortages, productivity, and occupational safety.

Keywords

Domain Ontology, Linked Data, Semantic Web, Robotics, Steel Fabrication,

1. Introduction

Within the contemporary construction industry, (partially) automated production systems are predominantly utilized for prefabrication processes. Nevertheless, the widespread implementation of automated production systems in steel construction is hindered by various factors [1]. These factors include geometric tolerances, material variations, component size and weight, and the fabrication of complex assemblies in small lot sizes. In comparison to other industries, steel construction encounters significantly greater component and manufacturing tolerances [2–5].

A transparent and continuous information process, as well as a standard for storing deviation and process information in an adaptive information model, is lacking. Machines can measure the real dimensions of single parts, but there is no defined place to provide feedback to the information model, and planning and fabrication data is not connected. Digitizing steel tolerance norms and developing an efficient interface for exchanging tolerance and process information can help implement Industry 4.0 concepts [6].

Therefore, our research aims to develop an ontology (refer to 2.2) that leverages semantic web technologies to describe steel construction information, including process information required for robotic processes, manufacturing process metadata, and feedback data such as quality measurements. By capturing critical deviations and resource-bound process parameters, we can improve efficiency and enable robotic workflows, while also exploring opportunities for process optimization. Semantic web technologies offer a continuous flow of information, connecting all stakeholders regardless of their software or machines. For this work, we do not focus on the steel detailing including planning and design, but rather the actual production process and it process information.

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2. Related Works

Steel construction has an industrial character and is primarily conducted through individual and small series fabrication [7]. The process involves planning, production, and assembly, which are spatially separated from each other. However, there is no centralized information model that combines data from all involved actors. While graphic or product interfaces can be used to transmit component information, they only provide geometric product descriptions without detailing production instructions. The most widely used data format in steel construction is the product interface DSTV-NC, which was developed by bauforumstahl [8, 9]. In Figure 1 an excerpt of the existing DSTV-NC schemata for the plane designations and the position of the coordinate system is displayed. The form elements of a part are assigned to the respective machining plane and positioned in the coordinate system of this plane.

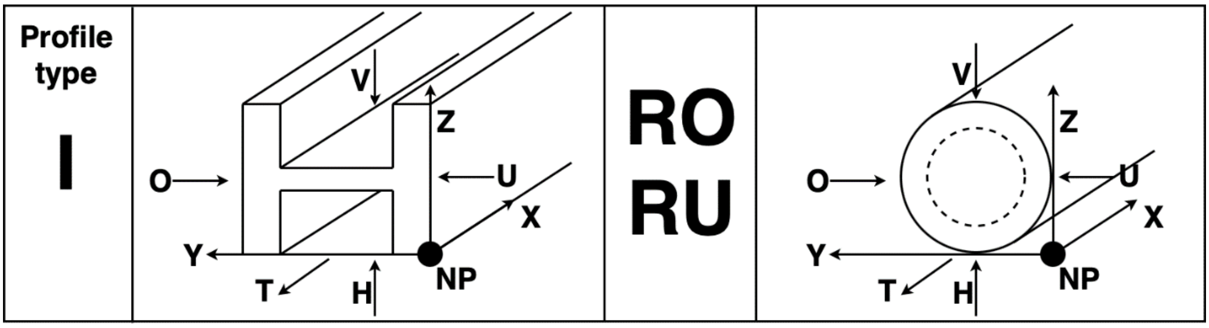

Figure 1: Redrawn DSTV-NC schemata for plane designations based on [9]

2.1. DSTV-NC standard as a base for robotic manufacturing

The steel construction industry relies on the DSTV-NC standard as an interface for CAD/CAM applications and Numerical control (NC) production. This standard enables the control of various NC machines, including drilling machines, flame-cutting and punching machines, and 5-axis CNC machining. To expand the use of robots in steel construction, an independent plugin for Grasshopper3d was developed to implement a prototypical interface for robot control based on DSTV-NC. The interface uses a task-oriented approach, in which a task corresponds to a machining step according to DSTV-NC, and a strategy is stored in the interface for generating robot code. A rule-based global path planning was developed to ensure collision-free machining of several sides of a component [10]. However, during the validation process, it was discovered that the DSTV-NC format lacks information on as-built dimensions, which poses a challenge for robot path planning. Because of this missing information the path plan must be manually synchronized and adjusted to avoid collisions between the robot and the part [11].

To address this limitation, there is ongoing work to transfer information from DSTV-NC into Industry Foundation Classes (IFC), which is the common exchange format for Building Information Modelling (BIM) data. This transfer could enable the operation and generation of machine code based on an IFC description of the desired workpiece. BIM is a method for creating and managing information for a building objects throughout its entire life cycle. IFC provides a standardized and open data format that contains extensive data structures for describing objects from almost all sectors, making it a potential alternative for storing additional tolerance and process information to enable robotic processes in steel construction [11, 12].

2.2. Relating Ontologies

Ontologies have emerged as a potential solution to address the problem of semantic interoperability [13–16]. They are formal specifications of concepts in a particular domain, often involving a logical theory and reasoning capabilities to deduce new knowledge [17]. Ontologies provide explicit data semantics, enabling semantic interoperability by representing entities, concepts, and their relationships in a clear and unambiguous manner [18].

In recent years, several ontologies have been developed for the construction domain. Most approaches have either involved translating existing models [19, 20], or developing new mapping techniques [21]. For describing general construction processes, work has been done in various research projects. The Internet of Construction (IoC) ontology revolves around the *ioc:process* concept, aimed at connecting different sub-domains of construction, including steel construction [21, 22]. The ifcOWL ontologies include the ifc:IfcTask class with properties to associate it with construction components, subtasks and resources. The LinkOnt extension adds terminology for task level and resource information. The MONDIS and CPM ontologies only cover inspection and repair. Then, the Construction Tasks Ontology (CTO) describes tasks associated with construction projects, such as installation, removal, modification, inspection, and repair. Tasks can be grouped using the concept of *cto:TaskContext*, and preventive maintenance tasks can fall under either repair or modification [23].

The ifcOWL-DfMa ontology is an extension for the ifcOWL ontology and aims to translate offsite construction domain terminology in a machine-interpretable way. As such, it is aligned with the ifcOWL ontology and developed so that every *dfma:Building* is an ifcBuilding. To fulfil the goal of the ontology to be used as a common reference model for offsite manufacturing, it is language independent and primarily separated into: DfMA_Production_Process (production and supporting activities), Resources (labour, material overhead and plant), Activities (production activities and resources) and Modality (platform, time, location and transport) [24].

El-Gohary presented a domain ontology for processes in infrastructure and construction (IC-PRO-Onto), which conceptualizes process-oriented knowledge. For example, it models activity-related constraints. The Digital Construction Ontologies (DiCon) is a suite of ontologies that serves as a unified representation of detailed construction workflows with associated entities and relationships. DiCon consists of six modules for specifying construction domain knowledge: Entities, Processes, Information, Agents, Variables and Contexts [25].

To support prefabrication and on-site assembly processes in construction, an ontology model was developed by Lee et al. to assist information handling while considering relevant component information such as geometry, material, and production speed. For model illustration, the interaction between components, materials, equipment and workers are described for off-site concrete panel prefabrication and on-site panel installation processes [26]. In this research, the approach of using ontologies for prefabrication in construction is built upon and further investigated. Lastra and Delamer proposed the use of ontologies to reduce engineering efforts for faster and cheaper set up of manufacturing production systems. Therefore, ontologies follow a modular and reusable approach to express the specific manufacturing domain knowledge. The base concept for the developed ontology evolves around the relation between the product, the process required to manufacture that product and the equipment that enables the process [27].

The key advantage of ontologies is that they can allow for the integration of established concepts, such as the DSTV-NC format, into the semantic web technology stack. This enables the linkage of heterogeneous and unstructured data, including various sources of information like BIM or scheduling data. However, previous works have primarily focused on describing general construction processes and have not focused on steel construction processes [28, 29]. There have been limited previous works on forming domain ontologies for this domain, resulting in the development of the DSTV domain ontology described below.

3. Methodology

3.1. Scope and Competency Questions

Our first approach to create the DSTV ontology was based on a direct translation of the XNC (XML) version of the DSTV standard (BFS-RL 03-105) [9]. The described information in the DSTV-NC was limited to workpiece information and the information concerning drilling processes which are defined in the standard as hl and hljob (from “hole”). This led to an OWL including 258 classes and 1583 Axioms. The result, only for this small fragment of the standard, proved to be overly complicated and completely unintelligible to the human reader. Therefore, the next iteration, which is presented in this paper, is based on rebuilding the ontology from scratch and adding the concepts existing in the standard only where needed. The aim is to simplify the concepts as much as possible and to reuse existing approaches wherever possible. The main method used for the development is described in "Ontology Development 101: A Guide to Creating Your First Ontology" by Noy and McGuinness [30]. Following the chosen guide, the first step for the iteration is to clarify the focus and scope of the ontology. To this end, three questions concerning the scope (SCQ) are defined and answered.

SCQ1 What domain should the ontology cover?

The domain of steel construction and steel fabrication

SCQ2 What is the purpose of the ontology?

The ontology should enable the description of a process chain to be used in steel construction and fabrication that also links measured deviations, tolerance and machine data. The ontology should help to model the processes using terms from the DSTVC standard so that concepts can be reused and easily mapped and aligned with the existing file formats of the standard.

SQ3 What kind of questions should the ontology be able to answer?

The ontology should describe the production process including the required data. This means that it should answer questions about the planned data and thus the basis for the execution of the process. In use, it should also allow the addition of measurement data, associated tolerances and validation information to answer questions about the adaptation of subsequent processes or quality control. The resulting datasets should be able to be used to optimize the production process.

Based on the specification of the scope, a set of competency questions (CQ) was developed, based on the previous contents of the standard, the results of interviews and exchanges with the industry partners of the BauFeSt project, and previous research results in the field of Linked Data. They can be found in Table 1 These competency questions are technical-functional in nature and describe what exactly should be able to be answered by queries once the ontology has been created. The scope of this paper focuses on CQ1-4, as CQ5-10 exceed the scope of this paper, need further development or are more related to the general process modelling approaches of the Internet of Construction (IoC) Process Ontology, which is being published in a Springer book this year.

Table 1

Competency Questions (CQ)

Type	**No.**	**Questions**
Plan data	CQ 1	What is the NC instruction I need to pass to the machine?
Measurement data	CQ 2	What are the measured values?
Tolerance data	CQ 3	What are the tolerances for the produced feature?
Validation data	CQ 4	Is the feature in tolerance?
Adjustment	CQ 5	Do I need to adapt following processes?
ifcAlignment	CQ 6	Is there an equivalent for my data in ifcOWL?
Intermediate	CQ 7	How does the intermediate „Version" of my element looks like?
Resource / machine	CQ 8	What machines and what tools are used?
Machine parameters	CQ 9	What are the process parameters used for the process?
Workflow	CQ 10	What is the production workflow or process chain?

3.2. Reuse of existing concepts

One of the principles of Linked Data is the reuse of existing ontologies. Our research into the state of the art of ontologies for steel construction showed that there are hardly any approaches to ontologies that have been developed for this domain. The competency questions cannot be fully answered in any of the available solutions, especially in a practical way for robotic usage. For concepts describing the construction process, building elements and element metadata, there are already ontologies that we consider to be applicable and mature. By including them, we hope to achieve greater interoperability. Table 2 gives an overview of the reused or linked ontologies.

Table 2

Overview of the connected ontologies

Namespaces	Main classes / focus and purpose of the ontology	Reference
bot	*bot:Zone, bot:Element, bot:Interface* Ontology describing the core topological concepts of a building and the relationships between the concepts. One of the central ontologies introduced within the Linked Building Data (LBD) group.	[28]
ifc	*Ifc:Root* Web Ontology Language (OWL) representation of the Industry Foundation Classes (IFC) schema	[31]
ioc	*ioc:process* Ontology developed within IoC to describe processes and process metadata	In print (not published yet)
opm	*opm:PropertyState* An ontology for describing properties that change over time	[32]
schema	*schema:Thing* Collaborative project to develop schemas for structuring data.	[33]

3.3. DSTV ontology structure and concepts

As the DSTV ontology is intended as a domain ontology linked to the top-level process ontology developed within the IoC project the ontology is centered around DSTV process classes which are subclasses of *ioc:process*. The *dstv:ProductionProcess* class can be derived from the initial standard. It's the basic description of a production process, stored in ASCII or XML based DSTV-NC files. To explain the structure Figure 2 shows an example of a *dstv:ThroughHoleDrill* (hljob) and its associated concepts.

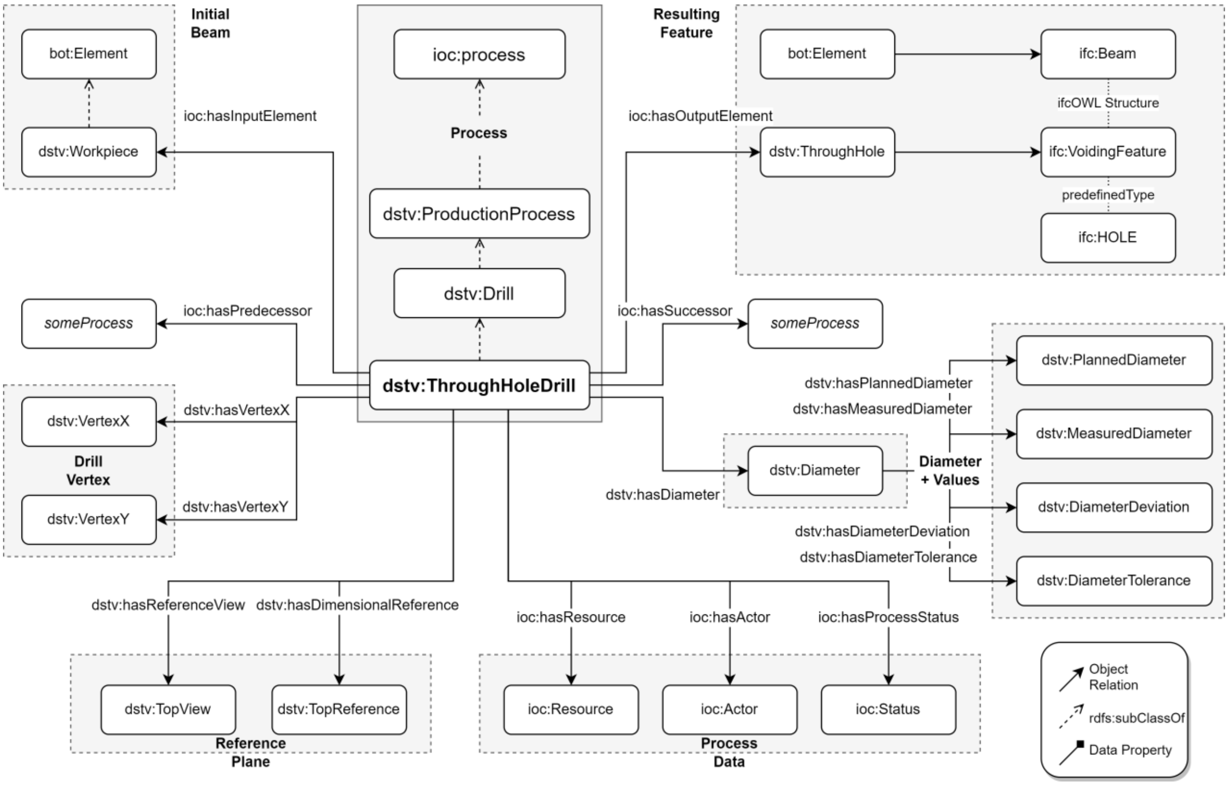

Figure 2: Concepts revolving a *dstv:ThroughHoleDrill*

The DSTV-NC standards as originally presented in the ASCII specification only covers the description of the incoming material (here: "initial beam"), the description of the reference plane and the description of the planned features to be produced. As the minimal use of the ontology should be to describe the same content as a DSTV NC file, relations and concepts that cover these in OWL were the first things that needed to be incorporated. Using the basic functionality of the *ioc:process* class, we can distinguish between element input and output, and therefore model the resulting feature of the process (*dstv:ThroughHole*). The feature can be mapped to a corresponding ifcOWL feature, in this case the ifc:VoidingFeature, which is a predefined type *ifc:Hole*.

Other concepts form the *ioc:process* superclass can be used to put the process in sequence (*ioc:hasPredecessor, ioc:hasSucessor*) as well as connecting process metadata such as Status or Actor. A special case here is the *ioc:Resource*, which describes the machine that is used for the process. The DSTV-NC standard describes a whole lot of metadata that can be connected to this concept. However, expressiveness is limited by the fact that this metadata is written in the file header which means that theses NC Files can only describe processes that are done by the same machine. This limitation can be easily eliminated by using a linked data approach. The metadata can be connected to a *dstv:Resource* class which needs to be included in further iterations of the ontology.

The main idea for extending the DSTV-NC standard to also include data about measurements, deviations and tolerances required to find a clean structure to describe the data and its interconnections. In the DSTV ontology, this happens via the main concept of *dstv:FeatureValues*. In the example shown in Figure 2 one of these is of type *dstv:Diameter*. Restrictions in OWL were used to model that every *dstv:ThorughHoleDrill* has exactly one diameter. The diameter can then be explicitly connected to values that state in their relation and ranged classes if they are planned or measured values, or if they represent a deviation or a tolerance.

The data from ASCII or XML based NC files are mapped to the planned values. The defined object Property for every subclass helps implementing validation via SHACL and keeps the data human readable. The data property is then connected via *schema:value*. This was done that in the next iteration concepts from the OPM ontology can be added.

3.4. DSTV extensions

3.4.1. Process Extension

As mentioned beforehand, the existing processes in the DSTV-NC standard all describe production processes. For all these production processes, the same logic as for the *hljob* or dstv:*TroughHoleDrill* can subsequently be applied. For extending it via the DSTV ontology, 3 additional process-types have been added.

dstv:MeasurementProcess describes measuring a feature value *like dstv:ThroughHole*. It has subclasses that directly correspond to every production process. Therefore there is a *dstv:ThrougHoleDrillMeasurement* class that can be related to a *dstv:ThoughHoleDrill*. This process adds a measured value to one or several feature values, that can be compared to a planned value. *dstv:ValidationProcess* describes calculating *dstv:DeviationValues* and comparing them to aligned tolerances. Depending on the output of this, a *dstv:AdjustmentProcess* can be executed which creates a new set of planning data for production process that come afterwards. The detailed structuring of these processes is especially useful if it is planned to use a multi robot cell for executing the whole workflow. Depending on the setup all these processes are done individually by different machines, algorithms or workers which need to be planned and scheduled to work together properly.

Figure 3 shows a use case for the extension in which all the process types mentioned are used in succession. The modelled case typically occurs in steel fabrication when there are two holes that are later used for a fitting. Here the position of the holes can vary to a certain extent, but the spacing must be precise. After drilling the first hole (*:ThroughHoleDrill_01*), a center point is measured and the deviation calculated. An adjustment process (*:ThroughHoleDrillAdjustment_01-02*) can query the deviation and use it to create a modified planned value for the second hole (*:vertexX_02*). This is also an example of a good use case where versioning with the OPM ontology would be beneficial.

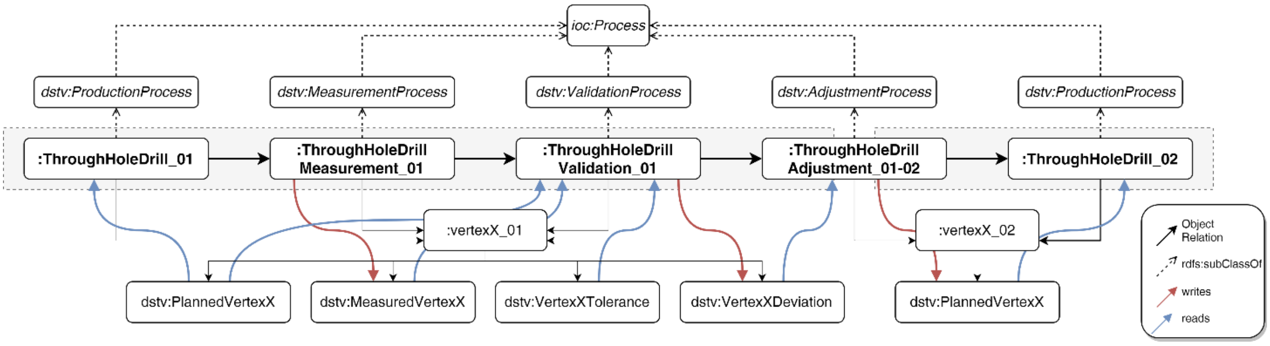

Figure 3: Process-types in a sequential use-case

3.4.2. Tolerance Extension

Tolerances are essential in defining the allowable deviations in dimensional and geometrical parameters of steel components such as beams, columns, and joints. They ensure that the different parts of a structure fit together correctly during assembly to provide the desired function, stability, and performance under load conditions.

Extensive research and personal discussions with steel fabrication experts have shown that some machines are already capable of automatically measuring the part before and/or after machining. However, because tolerances definitions only exist in human-readable files and prints, they must be entered manually by a user. This means that measurements cannot be validated against tolerances. Nor can they be stored.

As part of the BauFeSt project, research was carried out into the relevant manufacturing tolerances of various steel sections and the process tolerances of the drilling processes. The manufacturing tolerances of steel profiles describe the accepted deviations of the steel components themselves, e.g., profile heights, flange widths, web, or flange thicknesses. The standardized values for these tolerances can be found in relevant building codes, standards, and specifications, depending on the steel section. Manufacturing tolerances are based on DIN EN10034 for I- and H-girders, DIN EN10279 for U-beams, DIN EN10219-2 for cold-rolled hollow sections and DIN EN10210-2 for hot-formed hollow sections. Other process tolerances observed for drilling operations include single bore location, bore group location, distance between bore groups, bore ovalization, notching and bore diameter. They are described in DIN EN 1090-2, which sets out the requirements for the construction of steel structures.

The OWL-based extension of the DSTV-NC standard allows the inclusion and linking of production tolerance standards. This can act as an alignment between the presented ontology and other ontologies that should deal with the machine-readable description of these standards in the form of a knowledge base. In the context of the DSTV ontology, only min and max bounds have been included to ensure a minimum functionality for practical testing of the process logics.

3.4.3. Properties of the ontology

The ontology described here represents the second iteration of an OWL-based extension of the DSTV-NC standard. It covers only one of the seventeen process types described in the standard. In its current state, the ontology has 58 classes. There are 20 object properties, which are relationships between classes, and 3 data type properties, which are links from classes to data types and literals.

4. Evaluation and Use case

4.1. Initial Modeling

For evaluation, a sample machining operation was created that involves drilling 2 holes in an IPE 300 profile (see Figure 4). The used model was created and provided by an ad hoc working group for ongoing research into implementing DSTV-NC logic in the IFC data model.

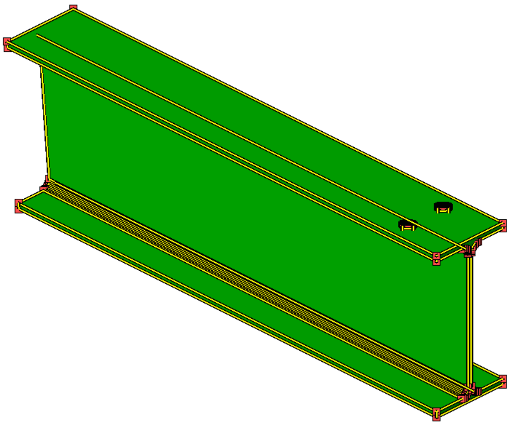

Figure 4: IfcBeam in the IFC4 File provided as well as its conversion in ifcOWL [Illustration by bauforumstahl e.V. - Ad-hoc Group DSTV-NC]

The IFCtoLBD [19] converter, which includes conversion via the ifcOWL ontology [34], is used to convert the supplied file to Resource Description Framework (RDF). For the storage of the created triples, an instance of the Stardog triple store is installed on the server of the university. The triple store provides a SPARQL endpoint for adding, modifying and querying the linked data in the graph. The original IFC4 file is 48KB in size. This corresponds to approximately 6100 triples stored in the triple store.

For evaluation purposes, the information concerning the DSTV processes was modelled manually. The Terse RDF Triple Language (Turtle) file created for this purpose contains 6 processes and their metadata, which add up to 149 lines of code including the prefixes used. The modelled processes were inserted into the database, which contains the description of the corresponding ifcBeam based on ifcOWL and the LBD ontologies. Table 3 shows an excerpt from one of the modelled drilling processes.

Table 3

Example of a modeled drilling Process

ttl

```
@prefix dstv: <http://w3id.org/dstv#> .
@prefix ioc: <http://w3id.org/ioc#> .
@prefix dstv: <http://w3id.org/dstv> .
@prefix inst: <http://baufest.org/dstv-test01#>   .
inst:DrillProcess_01 a dstv:ThroughHoleDrill;
    dstv:hasReferenceView inst:RefView_f_01;
    dstv:hasDimensionalReference inst:DimRef_t_01;
    dstv:hasDiameter inst:Diameter_01;
    dstv:hasMeasurement inst:MeasureProcess_01;
    dstv:hasVertex inst:Vertex_01;
    ioc:hasOutputElement inst:ThroughHole_01;
    ioc:hasSucessor inst:DrillProcess_02.
```

4.2. Querying

Since the structure of the proposed ontology is simple, querying the database to evaluate the formulated CQs proved straightforward. Table 4 shows a query written in SPARQL that was used to evaluate CQ1. Its basic application is to query the minimum data needed to write an NC command for a machine.

Table 4
SPARQL Query concerning CQ1

```ttl
PREFIX inst:  <http://baufest.org/dstv-test01#>
PREFIX dstv: <http://w3id.org/dstv#>
PREFIX ioc: <http://w3id.org/ioc#>
PREFIX schema: <http://schema.org#>
SELECT ?productionStep ?type ?referenceView
?referenceMeasurement ?diameterVal ?x ?y WHERE{
    BIND (inst:DrillProcess_01 as ?productionStep )
    ?productionStep a ?type;
        dstv:hasReferenceView ?referenceView;
        dstv:hasDimensionalReference ?referenceMeasurement;
        dstv:hasDiameter ?Diameter;
        dstv:hasVertex ?vertex.
    ?Diameter dstv:hasPlannedDiameter ?plannedDiameter.
    ?plannedDiameter schema:value ?diameterVal.
    ?vertex dstv:hasVertexX ?vertexX;
            dstv:hasVertexY ?vertexY.
    ?vertexX schema:value ?x.
    ?vertexY schema:value ?y.
}
```

Table 5 shows that the server response contains the required information. For better readability, the JSON object is presented in a table. Two sub-queries, not added here for simplicity, would need to query the transforms of the corresponding *dstv:referenceView* and *dstv:referenceMeasurement* nodes so that they can be used to describe the position of the holes globally, as would be required for a TCP frame-based robot manufacturing process.

Table 5
Server Response for the query shown in Table 4

ProductionStep	**type**	**referenceView**	**referenceMeasurement**	**diameterVal**	**x**	**y**
`inst:DrillProcess_01`	`dstv:ThroughHoleDrill`	`inst:RefView_f_01`	`inst:DimRef_t_01`	30	50	150

Replacing *dstv:hasPlannedDiameter* with *dstv:hasMeasuredDiameter* gives a measured value of 29.6 (millimetres), which shows that CQ2 can be answered. Querying the same diameter for *dstv:hasDiameterTolerance* and querying the values for *dstv:hasMaxBound* and *dstv:hasMinBound* gives an answer with -0.5 and 0.5 as tolerance limits. Thus, all information is available to calculate whether the feature is within the tolerance (CQ3+CQ4), which in this case is to be answered with "true".

Further tests of the possibilities to query the resulting database showed that the structure can easily be created from existing ASCII or XML-based NC files as well as from simple IFC descriptions. These tests are beyond the scope of this article. However, Figure 5 shows a more complex section of the graph used, showing that functions of ifcOWL and the LBD conversions are also included and can be queried following the logics introduced.

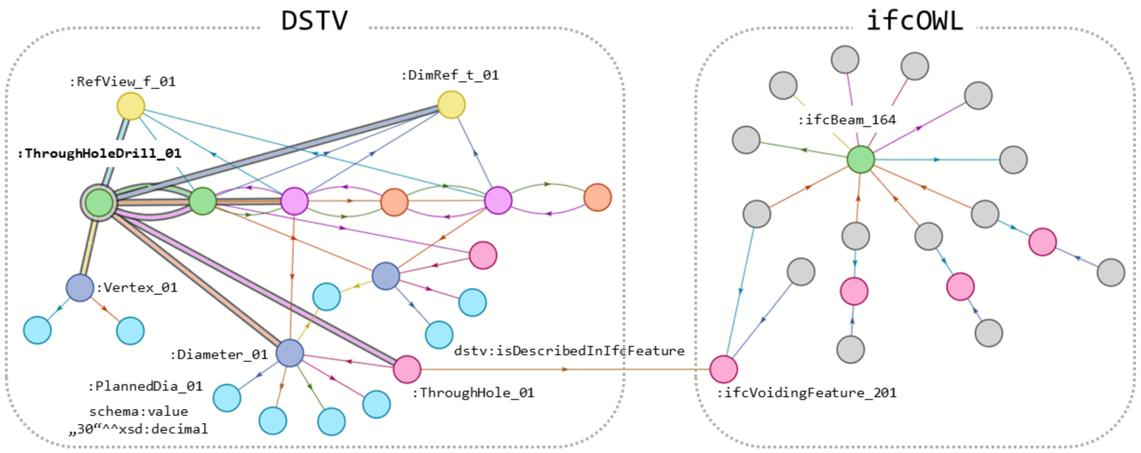

Figure 5: Simplified schema of the drilling-hole process graph

5. Outlook

5.1. Robotic manufacturing

In previous work, the requirement of linked process data, measured deviations and tolerances for the automation of steel construction was demonstrated with a robotic manufacturing process. To showcase the feasibility of the simplified and modified ontology for a robotic manufacturing process, a new use case on the base of the ontology will be conducted.

A Python script running on a web server automatically checks for the availability of all necessary information in the database and the status of the robot and tool when production is scheduled. If the robot and tool are ready, the script sends a JSON object containing robot control information to a KUKA | crc instance connected to the robot using the MQTT protocol. The robot interprets the commands and begins the process sequence. Following each process step, the robot sends a command to the web server to update the process status for that specific step. The timestamps generated from these updates can be utilized later to improve the movement and reduce the time required for the process. Subsequent, measurements and analysis of the work piece with 3D scanner offer real geometry data which can be added to the overall semantic web description (see Figure 6).

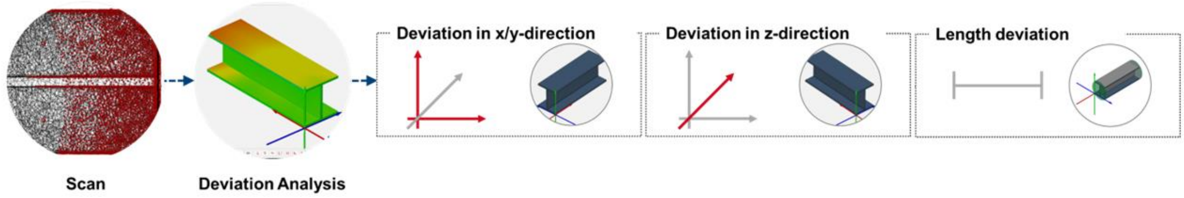

Figure 6: Deviation Analysis Pipeline with GOM Inspect

5.2. Future link and extension of DSTV Ontology

The development of the DSTV ontology allows the use of semantic web technologies for the description of steel construction information and therefore enables to link existing Linked Building Data approaches to steel construction processes. Additionally, it enables a robotic production process and an overall description of steel construction information. Including manufacturing process metadata such as tolerances and data feedback, the ontology can help tackle interoperability challenges. It can also be used to automate the evaluation of the measured data, as well as to analyze which tools cause which deviations from the planned geometry. The research could show that the optimization of processes based on real data is feasible and promotes more efficient steel construction processes.

In future research further links to ongoing works relating ontology developments for describing a type of manufacturing machine for Industry 4.0 systems can be drawn [35]. Semantic machine models may enable a central access for required machine data for manufacturing processes as well as capability matching for production resources and tools. Furthermore, the semantic web description of the steel construction process information may be linked to the ongoing work regarding an ontology-based manufacturability analysis for industrialized construction [36].

In further research, the proposed data model could be used to derive dependencies between process parameters and observed deviation and quality management data. In Addition, we also plan to include SHACL, so that workflows can be developed that enable validation that can be used for automated manufacturability analysis.

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