Establishment of a Guideline for the Intuitive Creation of Semantic Models in the Internet of Production (IoP)

Lina Teresa Molinas Comet, M.Sc.
lina.molinas.comet@rwth-aachen.de
RWTH Aachen University

Authors:
Lina Teresa Molinas Comet, M.Sc.
Iraklis Dimitriadis, M.Sc.
Patrick Sapel, M.Sc.
Prof. Dr. rer-pol. Stefan Decker
Univ.-Prof. Dr.-Ing. Christian Hopmann

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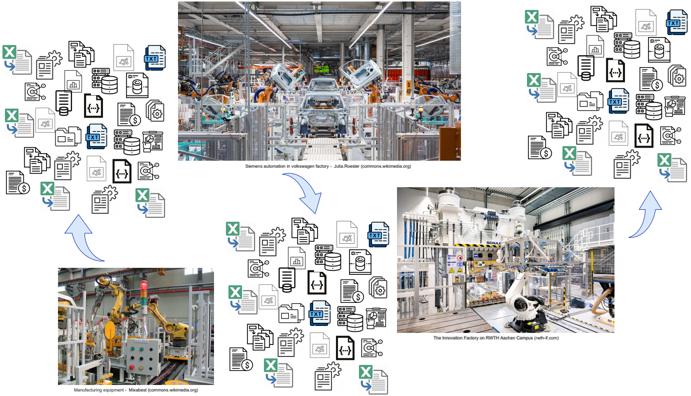
Agenda

- Motivation
- State of the Art
- Methodology
- Data Collection
- Realization
- Evaluation
- Contributions
- Future Work

Motivation and Background

Motivation - Background

Large amounts of data available in different representations



Siemens automation in volkswagen factory - Julia.Roesler (commons.wikimedia.org)

The Innovation Factory on RWTH Aachen Campus (rwth-if.com)

Manufacturing equipment - Mixabest (commons.wikimedia.org)

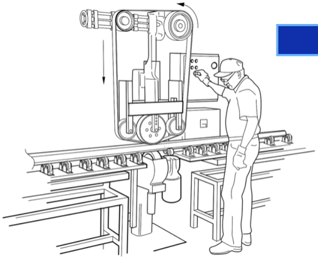
Motivation - Background

Internet of Production (IoP) cross-domain collaboration to enable a new way of data understanding by integrating semantics in real-time data related to the production system, including processes and user data [21].

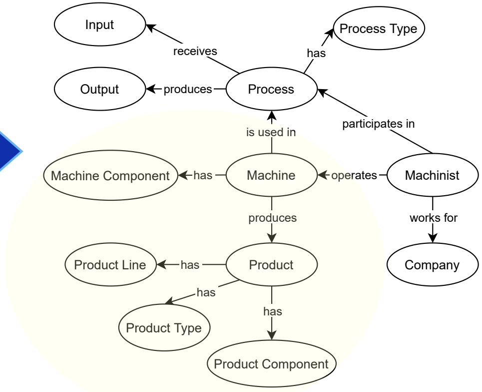
Motivation - Background

A semantic model is needed to describe all knowledge related to the production system, work-pieces, processes, and the environment.

Process Manufacturing

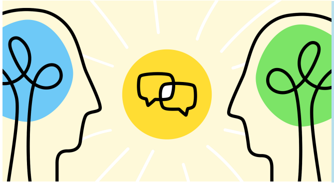


Semantic Model



Motivation - Background

Interdisciplinary task → Collaboration between Domain Experts (DEs) and Knowledge Experts (KEs) is necessary to create suitable semantic models



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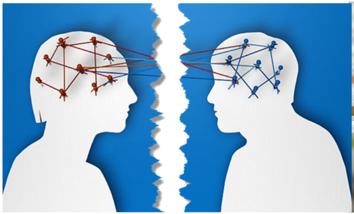
Motivation - Problems?

Task force of semantics in IoP detected some issues:

- Knowledge dependency from both sides
- Many guidelines but they are not intuitive or user-friendly
- There are not dedicated ontology libraries in our domain of interest



Research Questions

- When do we need to develop an ontology?
- What are the best practices to adopt in the ontology development process?
- How do we design more simple yet complete guidelines to allow domain and knowledge experts efficiently collaborate in the this process?

State of the Art

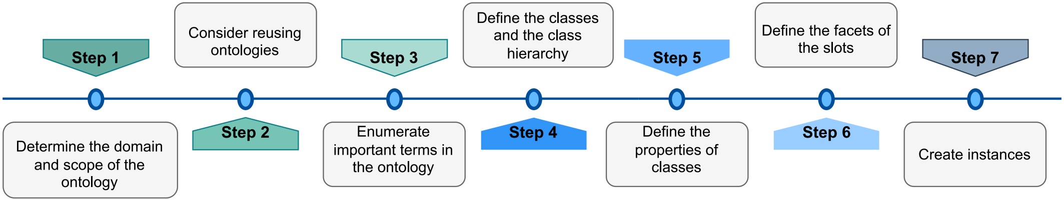
Ontology Development - Identified Problems

Ontologies are not yet widely adopted in the industrial domain [9, 19, 31]:

1. Domain Experts or decision-makers ignore the advantages of using ontologies to model knowledge
2. Hidden best practices in the literature
3. Lack of adequate tools supporting the ontology development (lack of compatibility, in some cases)
4. Limited assistance for creating or reusing ontologies
5. OWL language is complicated and has a broader coverage than semantic modeling (not frequently used)
6. Issues related to collaborative ontology development
7. Ontologies are usually big and segmented (hard to comprehend)
8. A curated list proposing the most suitable methodologies and tools for the ontology development process does not exist

Ontology Development - Common Steps

"Ontology Development 101: A Guide to Creating Your First Ontology" proposed by Noy and McGuinness in [14].



Methodologies for Ontology Development - Classification

There exist several classifications of these methodologies [1, 2, 9, 11, 17, 23]

Based on their Focus	Based on Collaboration Aspects	Based on their Perspective
• **Maintenance:** ∘ Focus on ontology maintenance ∘ TOVE, Methontology	• **Non-Collaborative:** ∘ Focus on the activities of the ontology development ∘ Do not emphasize collaboration between stakeholders	• **Waterfall-like approach:** ∘ Non-overlapping phases or steps ∘ More suitable for stable environments ∘ Depends on a clear rationalized engineering-based approach ∘ TOVE, DOGMA, EM
• **Preliminary tasks:** ∘ Focus on the preliminary tasks, including knowledge acquisition and scope ∘ ONIONS, MIRO	• **Collaborative:** ∘ Focus on the activities of the ontology development ∘ Emphasize collaboration among stakeholders (DEs, KEs) ∘ Continuos cooperation	• **Agile-like approach:** ∘ Flexible and adaptable to rapid changes ∘ Support adaptive collaboration ∘ Not always the best choice for large projects ∘ XD, AMOD, and RapidOWL
	• **Custom:** ∘ Stress the importance of collaboration among stakeholders ∘ More decentralized perspective ∘ Activities of the ontology development are described but not formally	• **Lifecycles approach:** ∘ Cover the entire ontology development life-cycle ∘ NeOn, DILIGENT, Methontology

Methodologies for Ontology Development - Selection

What is the "best" methodology for Ontology Development?

- Simple Knowledge-Engineering Methodology: (2003), clear steps facilitating the ontology development process [7]
- Methontology: (2015), it misses the design phase [10]
- NeOn Methodology: (2021), it focuses on best practices [30, 22]

Methodologies for Ontology Development - Selection

There is still no unified or unique answer

Methodology

Research Design and Methods

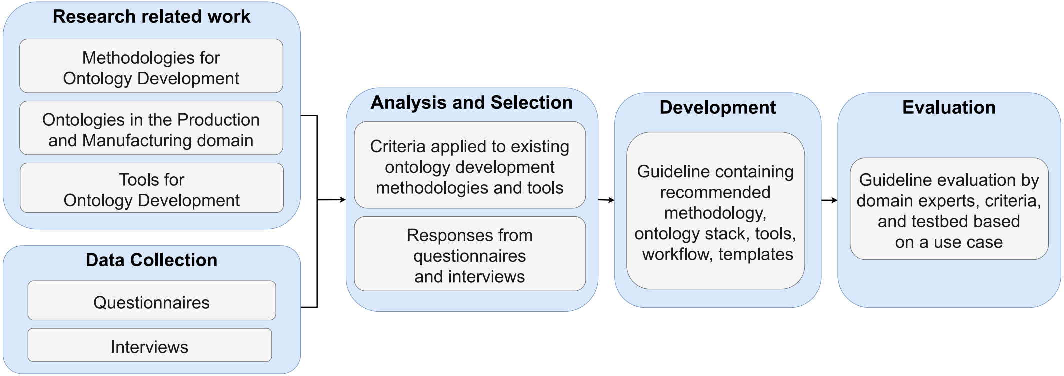


Figure: Methodology used in this work

Data Collection

Data Collection - Methodologies for Ontology Development

Steps 1 and 2: Literature Review and Methodologies Classification

35 methodologies and **10** general guidelines and principles to consider in the process

Step 3: Filtering and Selection of Methodologies

Approach	Focus	Agile	Year	REF
IDEF5	OntoDev, modification and maintenance	✗	1994	[78]
TOVE	Ontologies evaluation and maintenance	✗	1994	[60]
EM	Separate levels of formality	✗	1996	[187]
Methontology	Ontologies maintenance. Evolving prototypes	✗	1997	[51]
ONIONS	Ontologies acquisition	✗	1999	[53]
OD101	OntoDev steps and best practices	✗	2001	[118]
OTKM	OntoDev, maintenance and management	✗	2004	[172]
DILIGENT	Whole OntoDevProcess. Local vs global changes	✗	2004	[131]
HCOME	OntoDev and evaluation in knowledge work	✗	2005	[89]
UPON	Use-case driven, based on Unified Process	✗	2005	[40]
RapidOWL	Knowledge extraction, structure and processing	✓	2006	[12]
ODMPA	OntoDev in public administration domain	✗	2008	[24]
NeOn	OntoDev (Scenario-based)	✗	2008	[129]
DOGMA	Whole OntoDevProcess	✗	2008	[170]
XD	Problem space and solution space identification	✓	2009	[138]
OEM	OntoDev and maintenance (Process-oriented)	✗	2009	[173]
COLM	Ontologies maintenance	✓	2009	[100]
AMSACO	OntoDev in the business domain	✗	2010	[124]
KEADO	OntoDev of domain ontologies	✗	2011	[214]
OntoClippy	User-friendly OntoDev (tool-supported)	✗	2011	[37]

Data Collection - Ontology Development Tools

Step 1 and 2: Literature Review and Tools Classification

8 different groups of tools (Editors, Visualization, Documentation, Validation, Querying, Toolkits, Miscellaneous, More Technical) and **123** elements

Step 3: Filtering and Selection of Tools

Data Collection - Existing Ontologies

Step 1 and 2: Literature Review and Ontologies Classification

19 upper ontologies, **42** domain ontologies

16 supporting ontologies, **17** services to search for existing ontologies

Table 5.6: Existing upper and middle ontologies to consider in the OntoDev

Name	Focus	REF
SUMO	Linguistics, search, reasoning	[117]
OntoCape	Process engineering	[111]
BFO	Information retrieval, analysis and integration in various domains	[168]
Cyc	Concepts and rules about the world	[146]
PROTON	Semantic annotation and information retrieval	[31]
Sowa's	Logical, linguistics and philosophical concepts	[103]
UFO	Concepts about Philosophy, Linguistics, Cognitive Science	[63]
UMBEL	Subject concepts (a distinct subset of the more broadly concepts)	[212]
WordNet	Similar to a Thesaurus. Represent linguistic concepts	[120]
DBpediaOntology	Describes the concepts related to DBpedia	[11]
DOLCE	The intuitive and cognitive bias underlying common-sense	[21]
GFO	Categories such as objects, processes, time and space, relations,roles, etc.	[67]
KYOTO	Encode Natural Language concepts	[190]
YAMATO	Quality and quantity, Objects, Processes and Events, etc.	[109]
COSMO	Broad semantic interoperability	[62]
gist	Maximum coverage of typical business ontology concepts	[162]
MASON	Automatic cost estimation and manufacturing simulation	[162]
SIMPM	Model three fundamental constraints of manufacturing process planning: variety, time, and aggregation	[219]
MSDL	Represents conventional manufacturing processes	[87]

Legend: **MFG:** Manufacturing, **PROD:** Products, **PROC:** Processes, **RES:** Resources, **P.COMP:** Plant Components, **ACTV:** Activities, **SHED:** Scheduling, **MAINT:** Maintenance, **SENS:** Sensors, **ROBT:** robotics, **ENG:** Engineering, **BATCH:** Batch Processing, **MSMT:** Measurements, **STD:** Standards, **SIM:** Simulation

	MFG	PROD	PROC	RES	P.COMP	ACTV	SHED	MAINT	SENS	ROBT	ENG	BATCH	MSMT	STD	SIM	CLASSIF	REF
SOIL	✓	✓	✓	✓									✓			SM	[57]
SemAnz4.0	✓	✓	✓													SM	[119]
iFAB	✓															SM	[119]
ADACOR	✓		✓		✓		✓									SM	[119]
MASON	✓	✓	✓	✓												O	[15, 96]
MaSDeM	✓	✓	✓	✓							✓					O	[119]
SIMPM	✓		✓													O	[219]
PSL	✓		✓			✓	✓								✓	O	[15]
OntoCAPE			✓								✓					O, SM	[119]
BaPrOn			✓				✓					✓				O	[111]
FABMAS	✓	✓		✓		✓	✓									O	[110]
PrOnto	✓	✓	✓		✓											O	[119, 213]
ARUM	✓	✓	✓	✓			✓									O	[65]
RGOM	✓	✓	✓	✓			✓	✓						✓		SM	[213]
ONTO-PDM	✓	✓	✓	✓			✓							✓		O	[123]
MPMO	✓		✓	✓						✓						O	[28]

Ontology Modelling Languages - OWL vs SHACL

We present a comparison of both languages, based on [5, 6, 12, 16, 18, 20, 24, 25, 26, 27, 28, 29, 30, 32].

	OWL	SHACL
Type of language	Low-level	High-level
Complexity	Complex	Simple
Resulting models	Hard to understand	Easier to understand
Purpose	Encode semantics and allow inference	Encode restrictions to validate data
Common use	Reasoning	Validation
Approach	Descriptive	Prescriptive
Academic support	More books and academic papers	Usually focuses on the validation aspect
Tool support	More tools and software packages	Gaining more tool support
Vendor support	Limited and inconsistent	It is broadly supported
License	Open Standard	

Ontology Modelling Languages - OWL vs SHACL

	OWL	SHACL
Logic	Formal logic	Strong foundations in Description Logic [1]
Assumption	Open-World (OWA)	Closed-World (CWA)
Data structure	Graph-shaped RDF data	
Base technology	RDF	
Features	Properties and restrictions on them. No UNA	Shapes specifying restrictions. No object or data properties
Optimized for	Global systems	Local, closed systems
Expressivity	Very expressive	Rich and expressive
Soundness	Mathematically sound approach	Sound and complete for some SHACL fragments [2]
Decidability	Decidable, but not in a reasonable amount of time	Full language is undecidable. Decidability is possible for some restricted parts [3]
Extensibility	Not extensible, limited to the features included in the specification	Extensible because it allows to create own constraints types based on existing ones [4]

Refererences: [4], [13], [15] [12]

Requirements Elicitation - Analysis of Responses in the Surveys

Stakeholders from the Task Force Semantics IoP $\rightarrow$ **24** requirements

1. **Detailed workflow for ontology development**
2. **Modularity and integration with top-level ontologies**
3. **Iterative development practice**
4. **Close collaboration with domain experts**
5. **Use version control in the modelling process**
6. **Suitable tools**
7. **Use defined standards**
8. **Provide sufficient knowledge about ontologies and best practices**
9. **Application-oriented documentation and ontologies use**
10. **Unification of different guidelines**

...

Realization

Best Practices for Creating Guidelines

A generic guideline development process consists of applying the ADDIE model [8]

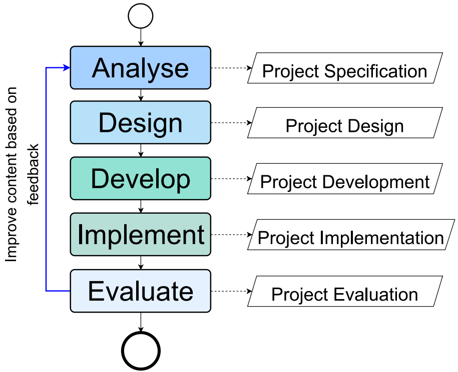


Figure: Phases of ADDIE model and our suggestion of continuous improvement based on feedback

Guideline for Rapid and Standardized Ontology Development

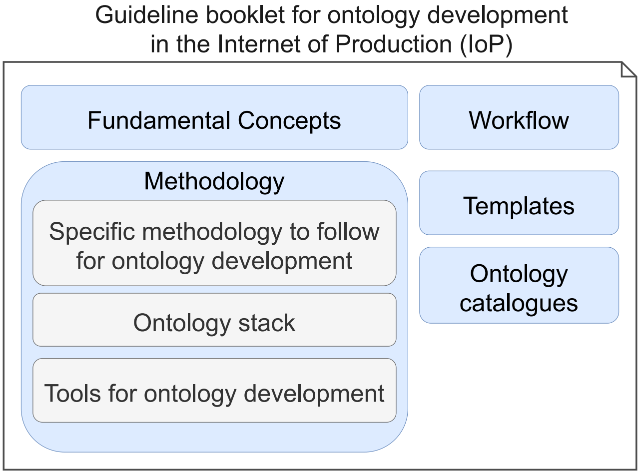


Figure: Structure of the guideline

Comparative Study of Methodologies - Possible Values for each Criterion

C_1. Detailed Guidelines About OntoDevProcess
The methodology includes detailed information about the ontology development process, with a detailed explanation.

C_4. Supports Ontology Reuse
The methodology recommends reusing existing ontologies and building the new ontology by integrating existing ones.

C_5. Methodology Type
The possible methodology types are Agile, Waterfall, and Lifecycle Support.

C_{21}. Technical Considerations
The methodology provides information about the more technical considerations, such as name conventions, domain and range, etc.

C_{27}. Close Collaboration With Domain Experts
The methodology includes information on how to closely collaborate with domain experts.

Possible Values for each Criterion

C1	C4	C5	C21	C26
3 Detailed	3 Clearly stated	3 Agile	N/A	3 Detailed information
2 Somehow detailed	2 Somehow stated	2 Lifecycles	2 Provides information	2 Some information
1 No details	1 No information	1 Waterfall	1 No information	1 No information

Figure: Some of the criteria identified as more important and the possible values they get

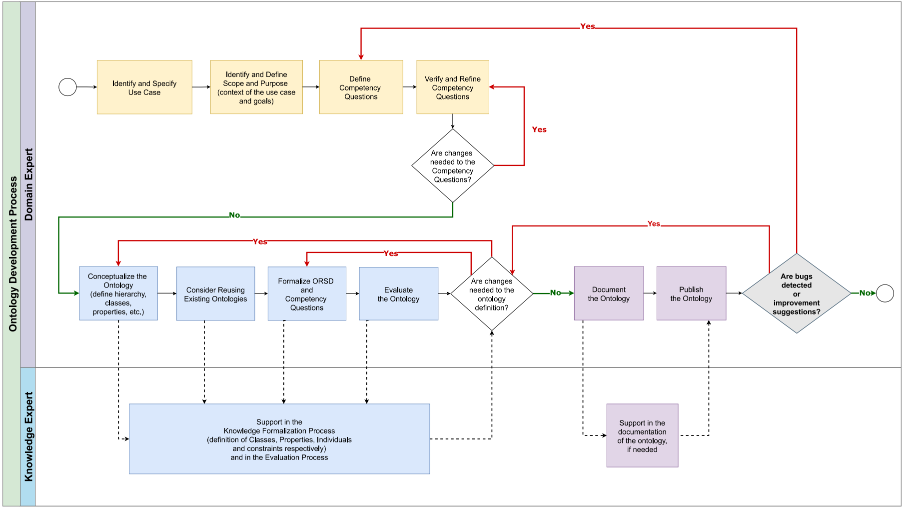
Comparative Study of Methodologies - Final Scores

Approach	*FinalScores*
LOT	98.5
NeOn	94
MOMo	91.5
AMOD	91
XD	86.5
YAMO	79.5
DILIGENT	78
MOM	77.5
SAMOD	77
XOD	76.5
UPON Lite	74.5
ODMPA	72.5

Approach	*FinalScores*
HCOME	71
UPON	69
OD101	68
KEADO	67.5
RapidOWL	66.5
OntoDI	65.5
COLM	65
OEM	64
MetROn	62
DOGMA	61
OTKM	59

Figure: Final scores for each methodology

Our Suggested Workflow for Ontology Development



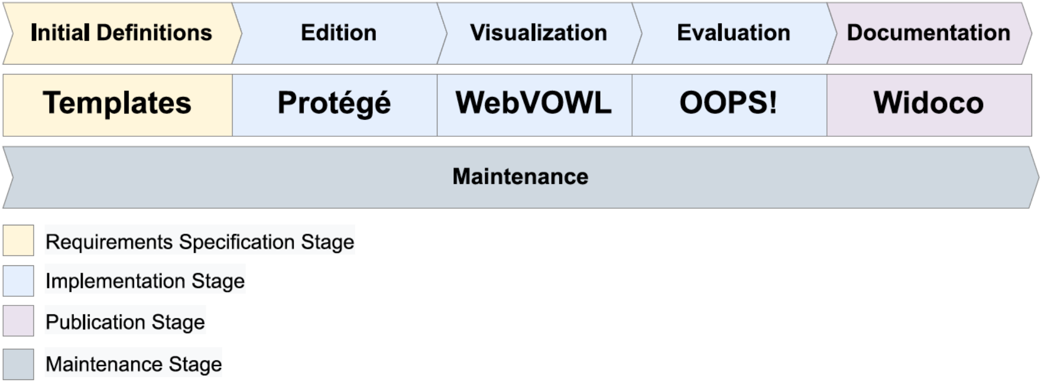
Unified Best Practices for Ontology Development

- Reuse ontologies
- Consider using Ontology Development Patterns (ODPs)
- Consider the quality requirements the new ontology should meet
- Focus on top-level ontologies to support consistent ontology development
- Adopt the top-down and modular approaches
- Specify disjointness of classes to help in the validation process
- Follow name conventions and keep it consistent
- Avoid class cycles

Comparative Study of Tools - Final Scores

	Tool	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	T_{Scores}
Editors	Protégé Desktop	1	1	2	1	1	2	2	2	1	2	15
	WebProtégé	1	1	2	1	1	2	2	2	1	2	15
	VocBench	1	1	2	1	1	2	2	1	1	2	14
	TopBraidComposer	1	2	2	0	1	2	2	2	1	1	13
	FluentEditor	1	1	1	1	0	2	0	1	0	2	9
Visualisers	WebVOwl	1	1	3	0	0	1	0	2	1	2	11
	VOWL	1	1	2	0	0	1	0	2	1	2	10
	OWLGRED	1	1	1	0	1	1	0	2	1	2	10
Validators	OOPS!	1	1	2	0	0	0	0	2	1	2	9
	Themis	1	1	2	0	0	0	0	2	1	2	9
	OntoDebug	1	1	2	0	0	0	0	1	1	2	8
Docs	widoco	1	1	2	0	0	2	2	2	1	2	13
	LODE	1	1	1	0	0	2	2	1	1	1	10
V. Control	GitHub	1	1	1	1	0	1	2	1	1	2	11
	GitLab	1	1	1	1	0	1	2	1	1	2	11

Comparative Study - Suggested Toolbox



Our Suggested Templates for Ontology Development

- We adapted existing templates to suit the needs of Domain Experts
- We designed templates to help define:
  - Competency Questions
  - Class, Property, and Individuals Definition
- They are based on templates used in automation tools (*OntoRat* and *Robot*) and the free available dataset of a benchmark of competency questions (*CQ2SPARQLOWL*)

Resulting Guideline Booklet

- **GitHub repository - LaTeX code**: `https://github.com/lcomet/UnifiedGuidelinesOntologyDevelopmentForIoP`
- **Guideline Booklet - pdf file**: `https://github.com/lcomet/UnifiedGuidelinesOntologyDevelopmentForIoP/blob/main/Guideline_OntologiesDevelopment_IOP-V3.pdf`
- **Templates available online**: `https://drive.google.com/drive/u/0/folders/1xwtJYaNQIGd1TWdWayciCiH5wcpnSDxw`

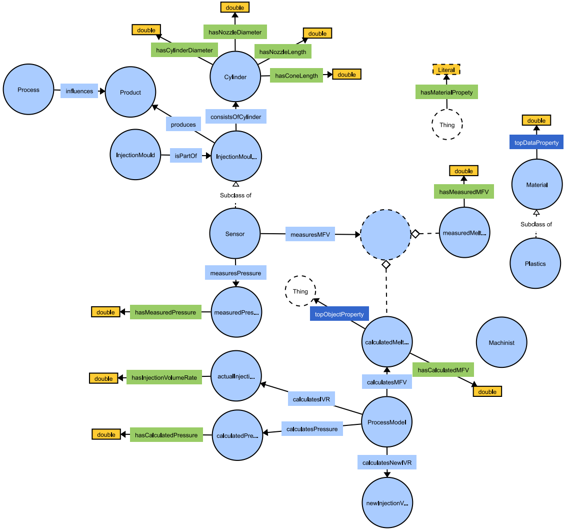
Evaluation

Evaluation by Testbed

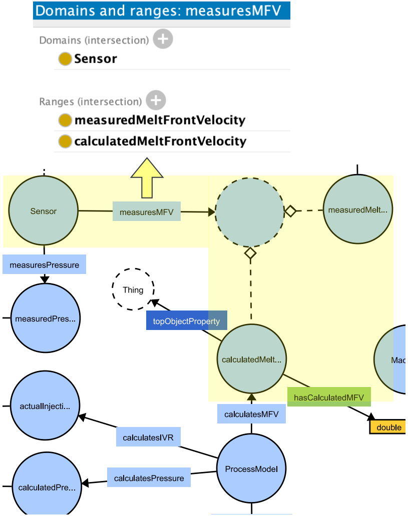
Use Case: “Optimisation of the Injection Phase"

Optimisation Objectives	
Improvement of part quality Increase productivity by faster and more objective process' set up	
Processes	**Attributes**
Injection Holding pressure	Geometry Material Mould Machine behaviour
Objects	**Constraints**
Injection moulding machine Injection mould Cylinder (diameter) Non-return valve Cylinder tip Plastic Material Viscosity pvT Simulation Process model	Temporal constraint Maximum pressure Maximum injection volume rate Maximum dosing volume

Evaluation by Testbed - Resulting Ontology



Evaluation by Testbed - OOPS! Tool - Critical Pitfall



Evaluation by Testbed - Workflow for Ontology Testing

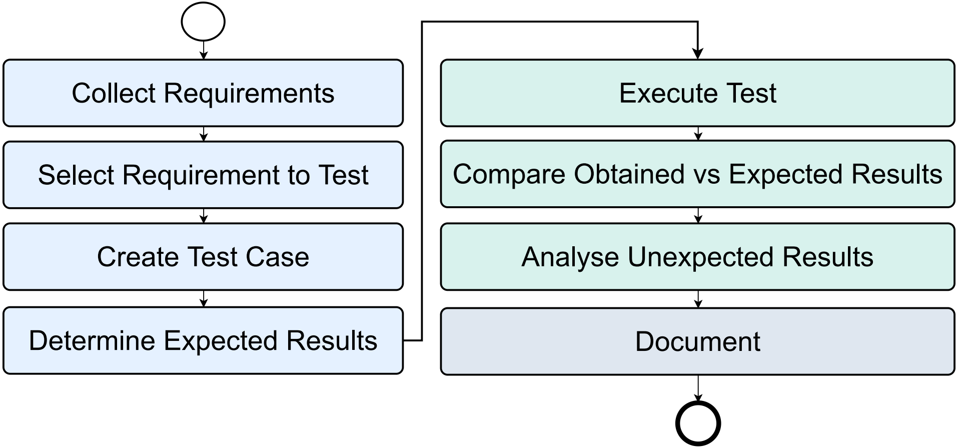


Figure: Steps to perform during the ontology testing considering Competency Questions, based on [3]

Evaluations - Summative Assessment

Good feedback indicating that our guideline contains:

- **Comprehensive and understandable information**
- **Clear examples**
- **Adequate information about tools and creation of ontologies**
- **Helpful templates**
- **Detailed workflow**
- **Unification of different guidelines**

Evaluations - Discussion

- Our guideline helps domain experts with no experience in semantic modelling to build ontologies from scratch
- It is a successful approach toward having a more fluent collaboration to create adequate semantic models in the IoP
- The guideline booklet can be improved

Contributions

Research Results

- Guideline booklet:
  - A unique guideline booklet covering the entire ontology development process
  - Helps identify when and how to use ontologies
  - Offers support to create more reusable and interoperable ontologies
- Studies:
  - Extensive study of methodologies for ontology development
  - Classification and Evaluation of methodologies, tools and ontologies
  - Study of alternatives to OWL for modelling knowledge

Improvements and Future Work

Future Work

- Guideline booklet:
  - Include more examples related to manufacturing use cases
  - Make guideline interactive and use engagement mechanisms
  - Based on project settings, automatically generate customisable workflows
- Tool Support:
  - Develop tools bridging the gap between domain experts and ontology development
    - Promising candidates: *Chowlk*, *Neologism 2.0*, and *WebOWL Editor*
  - Develop tools supporting SHACL as a modelling language

Future Work

- Studies:
  - Extend our initial work and build a curated collection of tools
  - A more systematic study, review and comparison of different domain ontologies
  - A more comprehensive study comparing OWL and SHACL for knowledge modelling
- Non-technical:
  - Create a central place for stakeholders to communicate more efficiently
  - Concentrate the knowledge on where, how to use, and how to integrate the ontologies in the IoP

Q&A

“I don’t pretend we have all the answers. But the questions are certainly worth thinking about."

— Arthur C. Clarke

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Appendix

Comparative Study - Criteria Based on Literature

C_1. Detailed Guidelines About OntoDevProcess
The methodology includes detailed information about the ontology development process, with a detailed explanation.

C_2. Use Of ODPs
The methodology includes information about the use of ODPs and recommends their use.

C_3. Supports Collaborative OntoDev
The methodology is suitable for collaborative ontology development and includes information on how to collaborate.

C_4. Supports Ontology Reuse
The methodology recommends reusing existing ontologies and building the new ontology by integrating existing ones.

C_5. Methodology Type
The possible methodology types are Agile, Waterfall, and Lifecycle Support.

C_6. Lifecycle Coverage
The methodology indicates the stages it covers in the ontology development process (ontology creation, ontology evaluation, etc.)

C_7. Defines CQs And Functional Requirements
The methodology indicates how to define competency questions and how to consider other functional requirements.

C_8. Supports Ontology Maintainability
The methodology indicates how it supports the maintainability of the ontology over time.

C_9. Supports Ontology Modifiability
The methodology indicates how it supports modifications in the ontology over time.

C_{10}. Supports Ontology Extensibility
The methodology indicates how it supports extending the ontology over time to cover new knowledge.

C_{11}. Recommends Tools
The methodology includes information on which tools and standards are more suitable for supporting the ontology development process.

C_{12}. Recommends Best Practices
The methodology includes information on the best practices to follow when creating and maintaining ontologies.

C_{13}. Supports Interoperability
The methodology supports the use of top-level ontologies and the integration of different ontologies.

C_{14}. Suitable For Different Users
The methodology considers different levels of knowledge and participation of actors.

C_{15}. Methodology Is Rooted In Previous Ones
The methodology builds on other approaches. It has taken into account previous methodologies and is based on them.

Comparative Study - Criteria Based on Responses

C_{16}. Suitability To Our Domain
The methodology is suitable for our domain. It can be used for developing ontologies in the manufacturing and production domain.

C_{17}. Provides Templates
The methodology provides templates to use in the ontology development process.

C_{18}. Specifies When To Build Ontologies
The methodology provides information on when to create ontologies, explaining the need for ontologies.

C_{19}. Covers Existing Ontologies In The Domain
The methodology recommends existing ontologies in the manufacturing and production domain.

C_{20}. Provides Examples
The methodology includes examples explaining the ontology development process.

C_{21}. Technical Considerations
The methodology provides information about the more technical considerations, such as name conventions, domain and range, etc.

C_{22}. Result Oriented Approach
The methodology defines deliverables for different stages of the ontology development process.

C_{23}. Covers Problem Definition
The methodology provides guidelines to help in the problem definition.

C_{24}. Examples Of Complex Ontologies
The methodology provides examples of how to model complex ontologies.

C_{25}. Modelling Alternatives
The methodology includes information on alternatives to model the same problem.

C_{26}. Well-explained Workflow
The methodology provides a well-explained workflow covering the ontology development process.

C_{27}. Close Collaboration With Domain Experts
The methodology includes information on how to closely collaborate with domain experts.

Comparative Study - Evaluation of Methodologies

$$C = \{set\ of\ all\ criteria\ for\ evaluation\ of\ methodologies\ and\ |C| = 27\} \tag{6.1}$$

$$\begin{gathered} W \subset C\ such\ that \\ W = \{C_1, C_3, C_4, C_5, C_6, C_7, C_8, C_9, C_{10}, C_{13}, C_{14}, C_{20}, C_{21}, C_{26}, C_{27}\} \end{gathered} \tag{6.2}$$

$$FinalScores = \sum_{c \in C} Score(c) \tag{6.3}$$

where:

$FinalScores$ is the final score based on both scores from literature review and responses to questionnaires I and II

$c \in C$, and C is set of all criteria

W is set of criteria we consider more significant

$$Score(c) = \begin{cases} \overline{s} \cdot score_c\ for\ each\ c \in C, & \text{if } c \in W \\ score_c\ for\ each\ c \in C, & \text{otherwise} \end{cases}$$

Comparative Study - Evaluation of Tools

$$T = \{set\ of\ all\ criteria\ for\ evaluation\ of\ tools\ and\ |T| = 10\} \tag{6.4}$$

$$T_{Scores} = \sum_{i}^{n} scoreT_i \tag{6.5}$$

where:

T_{Scores} denotes the total score per tool considering all criteria from the literature review and responses to questionnaires

$scoreT_i$ is the score of a single criterion $T_i \in T$ for all $1 \leq i \leq 10$