4th Conference on Production Systems and Logistics

Ontology-based Assistance System for Control Process Reconfiguration of Robot-Based Applications

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Abstract

Nowadays, production systems, and subsequently their automation and control procedures, become gradually more complex due to global competition and shortening product life cycles. To simplify the reconfiguration process for the worker, smart assistance systems are needed. The advantages of semantic technologies including ontologies, such as their graph structure and suitability for the use of optimization algorithms, illustrate their potential as the basis for a possible knowledge-based assistance solution. Against this background, the aim of this paper is to develop a concept for an ontology-based assistance system for control process reconfiguration that can consolidate existing product and process information and add expert knowledge to it. The focus is on the design of the ontology and the evaluation of possible SPARQL query-based assistance functions. To evaluate the tool, it is implemented on a use case of robot-based adhesive application and two possible assistance functionalities of the system are presented.

Keywords

Assistance systems; Semantics; OBDA; Optimization; Control process reconfiguration

1. Introduction

Due to increasing global competition, companies are challenged to make their production flexible and adaptable. This leads to a steadily increasing complexity of production systems and thus their automation and control processes [1]. At the same time, control processes must be quickly configurable in order to be able to react to short product life cycles. Downtimes of a plant due to reconfigurations cause high costs: In assembly lines such as automotive assembly, the costs of one minute of line downtime for reactive maintenance can amount to up to 20,000 euros [2]. Shortening the reconfiguration time in complex automation processes thus offers immense cost-saving potential, the actual implementation of which in business reality represents a major challenge.

Robot-based adhesive application in automotive body assembly represents one such control and automation process. In car body assembly, industrial robots are increasingly being used for gluing side panels, enabling flow operation in assembly. In the event of a functional change in the production process, such as the replacement of the adhesive to be used, all the given process interrelationships must be analysed again and reconfigured if necessary in order to ensure the quality of the bonded joint. Comprehensive data management systems that provide an overview of all the system parameters and control levers are often not available in companies, so that reconfiguration is based on experience [3]. Correct adjustment of the process parameters thus requires the user to have precise knowledge of the complex interrelationships between the process and bonding parameters and their effect on upstream and downstream process steps. This makes the search for solutions in the event of a process change more difficult and time-consuming. In order to master the complexity of process planning and configuration, a large number of user-supporting solutions exist in the

DOI: https://doi.org/10.15488/13444
ISSN: 2701-6277

area of product lifecycle management (PLM). However, these neither have the functionality to generate solution and optimization proposals, nor do they map the existing expert knowledge with so-called empirical values about the system behaviour [4]. The advantages of semantic technologies including ontologies, such as their graph structure and suitability for the use of optimization algorithms, illustrate their potential as the basis of a knowledge-based assistance solution [5].

Against this background, the aim of this paper is to develop an ontology-based assistance system that can consolidate existing product and process information and add expert knowledge to it. For this purpose, production-related assistance tools are presented in Section 2, along with common database management systems and ontologies. Based on this, a concept of a semantically based assistance tool is presented in Section 3. Section 4 describes the present robot-based use case on an exemplary implementation is based on, described in Section 5. In Section 5, two exemplary functionalities of the assistance tool are illustrated: a search functionality for necessary process parameter adjustments in dependence of the used adhesive and a selection aid for the adhesive to be used based on existing system boundary conditions. The paper concludes with a summary and outlook on further work in the presented field of research.

2. State of the art

2.1 Production data management systems

Data management systems and information models can be used to secure, manage and model data. In the production environment, database management systems (DBMS) and the Open Platform Communications Unified Architecture (OPC UA) are commonly used for this purpose .

The DBMS represents a software system for creating and maintaining databases. This includes the creation and manipulation of databases, enabling logically structured storage and manipulation of data by users [6]. In the field of production technology, most commonly used database system is the relational DBS (RDBS) [7]. This is represented on the one hand by a database, which from a mathematical point of view is a table-based relational database model and on the other hand by the descriptive query and manipulation language Structured Query Language (SQL) as DBMS [8]. The object-relational database system (ORDBS) is a special form and further development of the RDBS and has gained acceptance in recent years due to its object-oriented approach [9]. The basic idea of the object-relational database system is to link object-oriented programming with the relational database approach. This in turn enables the modeling of complex relationships and the creation of a structure within the ORBDS. Nevertheless, due to insufficient relations, this kind of data modeling is not sufficient to create a higher-level and universal schema for derivable knowledge [10].

An alternative option to data modeling in production systems is information modeling using OPC UA standards. Information modelling with OPC UA offers the possibility to semantically model versatile data relationships in a uniform way, especially with the help of the so-called Companion Specifications. Nevertheless, due to the lack of interfaces for browsing and deriving knowledge from information models, this technology is insufficient for modeling a coherent knowledge base of a consolidating assistance system [3].

2.2 Semantic technologies in production

To model a knowledge base in the production environment, data needs to be extended by means of semantics [11]. Following the Semantic Web rules, the data can be interpreted by a machine [12]. In this context, interpretability for machines means that data is linked to other data by means of relationships, thus generating an explicit knowledge base. This can be processed by machines as well as made accessible to humans. For semantic enrichment of data, the Resource Description Framework (RDF) is used as a standardized syntax and core technology. Since a uniform and declarative structure in RDF was missing, the RDF Schema (RDFS) was introduced. These technologies enable semantic modeling of contexts. When merging many so-called RDF and RDFS statements, the resulting graph has to be made readable to the machine. This happens by means of different serializations, which specify the data format and thus the syntaxes [13]. The respective syntax can be used for the Ontology Web Language (OWL) as data format and represents the essential OWL ontology. OWL enables the complex modeling of relations with additional features like cardinalities or inverse relations [11]. Thus, ontologies using OWL create a suitable data modeling for complex relations and enable the intelligent derivation of knowledge. Furthermore, suitable modeling allows flexible adaptation and transferability to other data models. However, initial modeling is associated with high effort. To address this problem and ensure reusability, modelling should be based on existing approaches. In the following, some chosen upper ontologies are presented, which can be designed as a transferable knowledge base and adapted for diverse production systems, thanks to their basis structure.

The *Suggested Upper Merged Ontology (SUMO)* is an ontology aggregated from a set of Upper Ontologies and serves as a standard document for the further development of specific ontologies [14]. Among other things, SUMO serves as the foundation for the Robotics and Automation Ontology Core Ontology for Robotics and Automation (CORA) as well as the Position Ontology (POS) [15]. The SUMO ontology can also be used as a base to integrate other previously non-standard ontologies.

The usage domain of the *Core Ontology for Robotics and Automation (CORA)* is the integration of robot-specific applications and was created by an aggregation of already standardized and non-licensed ontologies for robotics and automation into one [16]. By incorporating CORA, an ontology for robotics-based and automated production processes can be developed. This Upper Ontology extends SUMO and creates a basic architecture for robot-based systems.

To be able to model information regarding trajectories and coordinate points, SUMO and CORA are extended by *POS (Position) Ontology*. The POS ontology is on the same ontological level as CORA and can represent the position of robots in qualitative or quantitative orientation [15].

Temporal processes are not able to be modeled with the SUMO, CORA, and POS approaches. For this purpose, the *OWL Time Ontology (TIME)* is considered. The TIME ontology represents a recommended W3C candidate for standardization and is used for describing and ordering temporal relations between temporal instances and intervals. Different time formats as well as durations can be implemented with this approach. Moreover, the temporal consideration of resources (URI) can proceed both time-relative and absolutely [17].

In addition, Ontology-Based Data Access (OBDA) approaches are increasingly being used in production engineering. The goal of the OBDA strategy is to give users the ability to directly query data that is dispersed over numerous distributed sources, such relational databases. The mapping layer of an OBDA system converts user questions from a familiar ontology vocabulary into the vocabulary of the underlying data sources, and then transfers responsibility for query evaluation to the data source's appropriate query answering system [18].

2.3 Assistance tools for control process reconfiguration

A current approach to reducing the complexity of reconfiguration processes in production is the use of Decision Support Systems (DSS) for the worker. This is achieved by deriving and displaying information from a knowledge base. In the industrial environment, applications such as Mechatronic Concept Designer and Tecnomatix from Siemens are commonly used. The Mechatronic Concept Designer can accelerate constructive processes by means of simulation as well as by representing information about robot control parameters. However, it is not currently possible to derive a recommendation for action here. The system serves to visualize interrelationships to offer the user the possibility to design processes already during development and thus, for example, to determine process sequences [19]. Tecnomatix offers similar functions and was designed for factory planning applications. Process sequences can be simulated with the tool to see the process result of some pre-set parameters. Through extensions in the application, simulative movements can be implemented and thus a plausibility check can be performed. Also in this case, however, no fully automatic recommended action can be derived for the end user [20].

Recognizing the lack of derivation of a recommended action in the industrial environment, research created a system based on Bayesian networks that can be used to diagnose faults in production equipment. This system calculates the probabilities of triggers of a fault or solutions to it by estimating the probabilities of occurrence, expert knowledge, and available data. Depending on the interaction with the system, the probabilities can be subjected to a learning process so that the system makes better predictions. The drawback to this system is its specific use case. Although the system can derive initial recommendations for action when errors occur, it cannot be extended with further functionalities based on the same knowledge base. Thus, the generated knowledge base is not reusable [21].

To address the problem of reusability, there is some research on ontology based DSS approaches. [22] describes systems for troubleshooting, for energy consumption reduction of oil and gas companies, for network security systems and for medical decision support. In these cases, ontology-based knowledge base is developed, which is extended by means of data and semantic correlations. This knowledge base is searched for explicit knowledge by the systems in order to derive insights. With the help of these insights, decision-supporting actions can finally be extracted. However, none of these application fields are in the production engineering environment, despite promising success.

[23] contains a detailed description of common application areas of semantic technologies in production engineering. It distinguishes between five areas: Data/Service Catalog, Integrating Domains, Database Access, Consistency and Reasoning and Data Aggregation, with Data Service Catalog being the most common application. The examples show the feasibility of complexity modelling of the entire system, which can be used to search for necessary parameter relationships. However, all the systems has a descriptive role and do not have the functionality of intelligent solution proposals for producing optimal production plants.

In summary, it can be stated that semantic approaches to support the user exist in various production sectors, but mostly only serve to consolidate the existing process knowledge. Today, there are hardly any semantic tools on the basis of which intelligent solution proposals can be generated.

3. Concept development

Based on the findings from the previous Sections, there is a need for knowledge-based assistance systems for control process reconfiguration that could reduce the time required for this. Such a system should be able to cope with two relevant challenges: on the one hand, the integration of existing expert knowledge and, on the other hand, the need to generate intelligent solution proposals. Both of these issues might potentially be resolved using semantic technologies: first, by building a comprehensive system knowledge base that includes expert knowledge; second, by providing intelligent support when looking for configuration options.

By establishing new relationships between the data points of remote data resources, an ontology-based configuration tool can integrate currently existing product and process information, enhance it with expert knowledge, and reveal new knowledge linkages. The accumulated knowledge can then serve as the foundation for help programs that optimize process configuration. They can speed up user solution search and reduce planning and configuration time.

The anticipated approach for creating an assistance system for knowledge-based control process reconfiguration is shown in Figure 1. The design of the knowledge management system is a crucial component of the solution hypothesis. The knowledge management system's model specification is carried out using the requirements description (A). This involves analyzing and using as a system base existing methodologies for semantic modelling of robot-based processes, such as CORA, POS and TIME, s. Section 2. The system's potential connections to internal data sources are then investigated (B and C). The evaluation of the created process interface's integration potential with the production process' OPC UA information models is of increased significance (B). Preliminary work for this connection is described in [3]. Additionally, the integration of the current expert knowledge into the system to be constructed in the form of machine-readable, interpretable metadata is the primary factor to be taken into account (D). Finally, it is proposed that the knowledge management system might be integrated into a future, comprehensive semantic network of the Internet of Production (F). This line of research has already been dealt with in detail in [10].

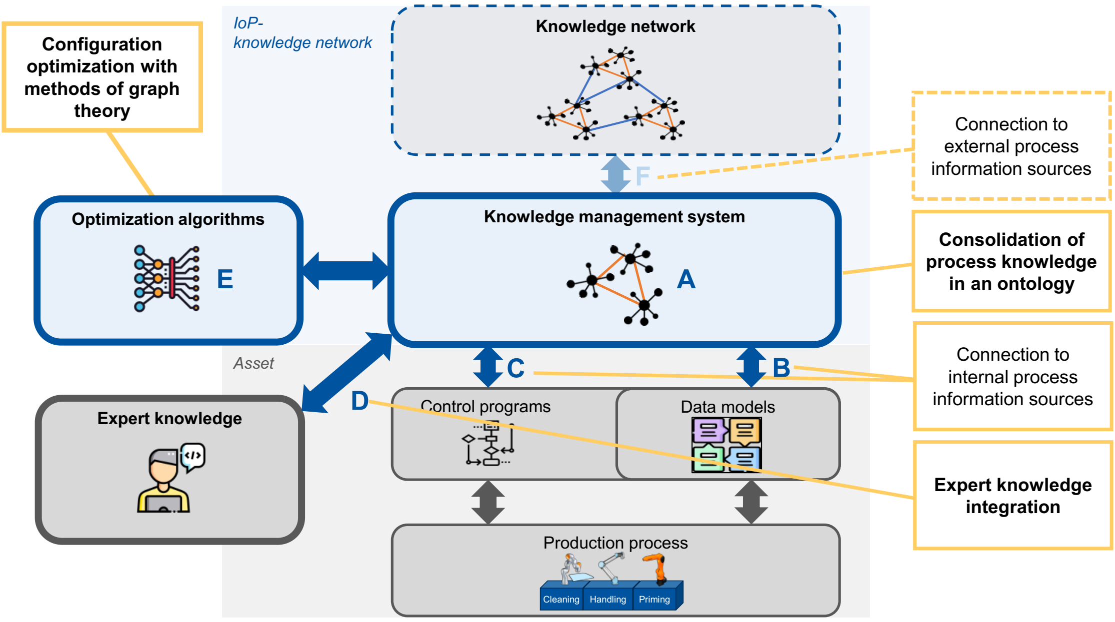


Figure 1: Concept of an assistance system for knowledge-based control process configuration

In the context of this paper, the design of the consolidating knowledge management system (A) and a possible connection of the existing expert knowledge (D) are considered in particular. Based on this, an initial assistance system is to be created that is able to provide the user with solution suggestions for adjusting the parameters. The solution suggestions are to be based on SPARQL queries of the given knowledge graph of the knowledge management system, because the results can be easily processed sequentially.

4. Use Case

Figure 2: Robot-based glass pane completion use case

The idea is put into practice in a robot-based glass pane assembly sub-process, shown in Figure 2. The stations Cleaning, Handling, and Priming make up the sub-process. The first station simulates the procedure of cleaning the working trajectory of a car window. Here, the glass's shape is cleaned with a KUKA iiwa. A KUKA Agilus (KR 6) is utilized in the priming station to apply glue to the glass pane's cleaned shape. The two stations each have a workpiece carrier that the disc is securely mounted to and a proximity sensor that allows the positioning of the disc to be watched. The panes are switched out and passed from station to station by the handling robot (UR 5).

One of the major challenges of the process is the multitude of adhesive and process parameters, such as the flowability, the bead cross-section or the travel and adhesive exit speed, which are interrelated in many complex ways. A correct setting of the process parameters requires the user to have precise knowledge of the interrelationships between the process and bonding parameters and their effect on upstream and downstream process steps. This makes the search for a solution in the event of a process change and more difficult and thus the downtime for reconfiguration time-consuming.

5. Implementation

To implement the concept, a basic architecture of the assistance system was created according to the concept shown in Figure 1.

Process and machine data are extracted and processed. The extraction is done by the combinatorial use of TCP/IP sockets and SFTP, as well as the use of OPC UA communication standard. The extracted data is extended by individual algorithms, classified and secured by means of an ORDBS. Subsequently, the process ontology presented in the following can be modeled based on the ontology standards described in Section 2. Finally, through an Ontology Based Data Access (OBDA) approach, components of the process ontology can be connected to the data in the ORDBS data model. This results in a Knowledge Graph as a knowledge management system, which serves as a decision-making basis. The user can interact with the system via a front-end application. A focused view of the process ontology and the Knowledge Graph are presented in the following.

5.1 Basic ontology for production processes

First, the basic ontology is implemented on the basis of the findings from [15] (s. Section 2) . For this purpose, the SUMO, CORA and POS architectures are adopted and modeled. Consequently, the TIME ontology is integrated into the architecture. It is important to mention that the Upper Ontology logic must not be violated. For this reason, the TIME ontology is placed on the same level as CORA and POS ontologies. Since time has no spatial elements, the ontology must be classified under Abstract. Figure 3 represents the complete basic ontology without associated object and data relations of the TIME ontology. These can be chosen variably depending on the use case.

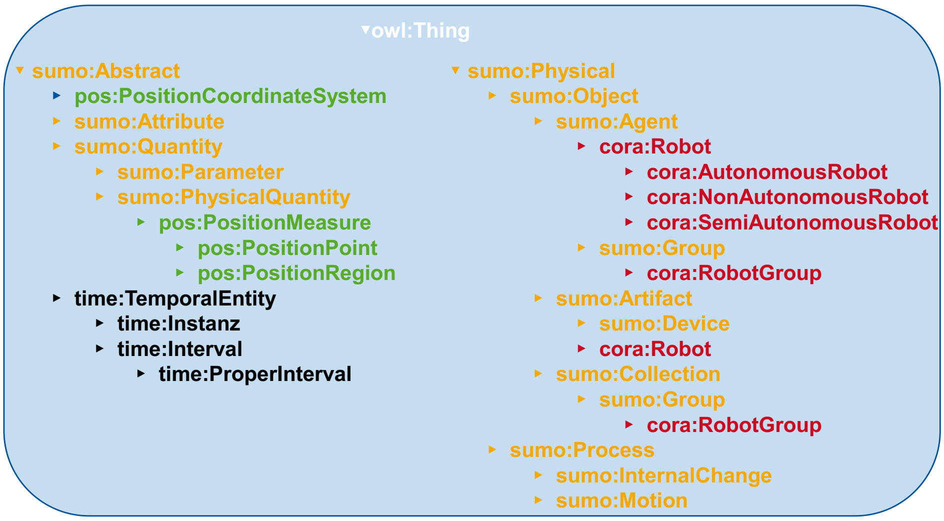


Figure 3: Upper ontology class hierarchy

This ontology can now be used as a basis model of a production process. By choosing this architecture, ontologies representing distributed processes or developed by multiple people can be adapted and combined adaptively and flexibly. For the described use case, the basic ontology is extended by use case specific

Classes, Object relations, Data relations and Instances. Furthermore, an OBDA mapping is applied to assign values to selected Classes and Instances, according to [7]. In the following, two exemplary use cases are considered that demonstrate the smart assistance service with the conceptualized system: first, a parameter adjustment for adhesive change and second, adhesive selection based on system boundary conditions.

5.2 Assistance case 1: Parameter adjustment for adhesive change

The gluing result is largely determined by the interaction of the robot speed and the volume flow, which can be calculated from the pump pressure and drive power, pressure reduction and overflow valve parameters and the density of the adhesive used. There are correlations between the settings of the individual parameters, e.g. between the maximum possible pump pressure, the viscosity and thus the density of the adhesive. Therefore, parameter adjustment after adhesive modification is a major challenge because of this large number of parameter correlations that are not directly apparent and can be influenced by the modification. However, this can be overcome insofar as expert knowledge is mapped in a knowledge graph. For demonstration purposes, two adhesives with associated parameters were linked via a *:hasParameter* object relation , s. Figure 4. The parameters are also associated with a controlling instance indicating the influence on the parameter, and an associated value is assigned using the OBDA approach.

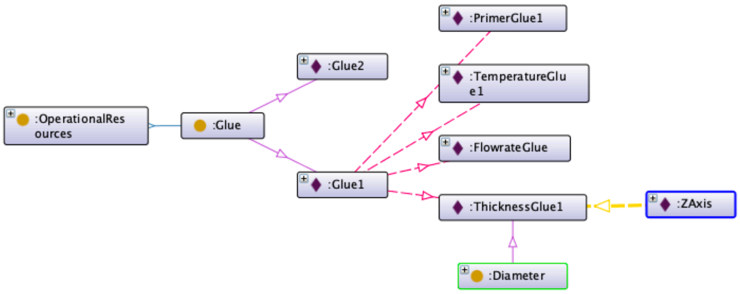
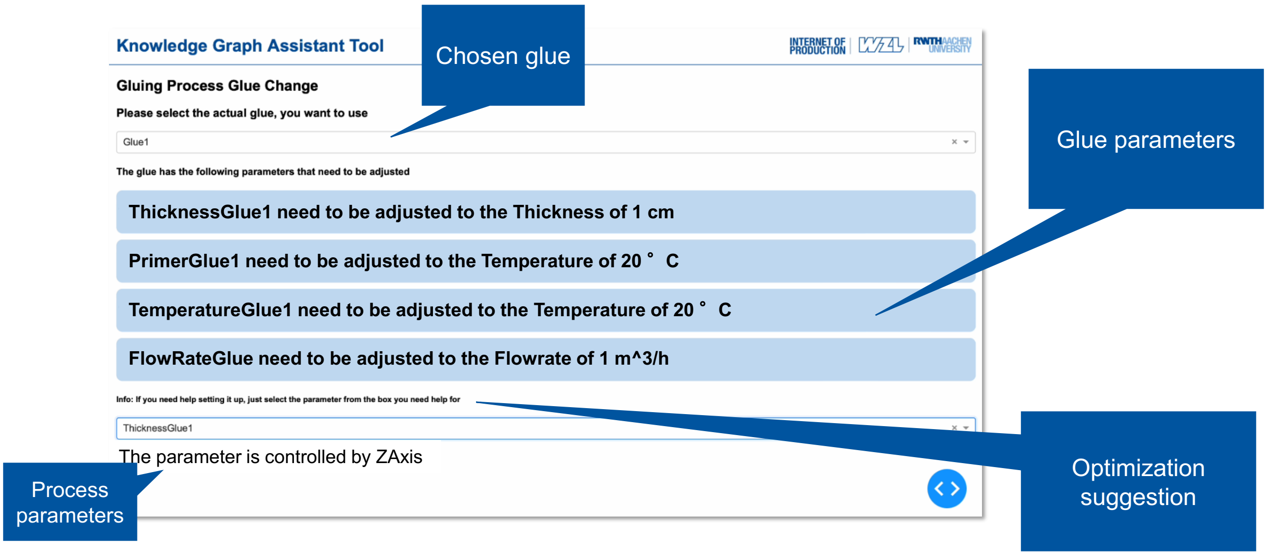


Figure 4: Parameter adjustment for adhesive change: Knowledge Graph extract

The web application of the assistance system can now access the knowledge graph via an endpoint, which is provided by the OBDA approach, and first extract the process components of the "Glue" class using SPARQL. Afterwards, the user is given the possibility to select the desired glue via an interface. Based on the input, the search engine of the tool extracts all parameters found and outputs them with the stored values. If the user requires setting assistance, the controlling parameters can be queried. These represent the software or physical parameters and variables to be set. Figure 5 shows the graphical user interface of the developed tool.



Knowledge Graph Assistant Tool

Gluing Process Glue Change

Please select the actual glue, you want to use

Glue1

The glue has the following parameters that need to be adjusted

ThicknessGlue1 need to be adjusted to the Thickness of 1 cm

PrimerGlue1 need to be adjusted to the Temperature of 20 ° C

TemperatureGlue1 need to be adjusted to the Temperature of 20 ° C

FlowRateGlue need to be adjusted to the Flowrate of 1 m^3/h

Info: If you need help setting it up, just select the parameter from the box you need help for

ThicknessGlue1

The parameter is controlled by ZAxis

Figure 5: Assistance case 1: Graphical user interface

5.3 Assistance case 2: Adhesive selection based on system boundary conditions

The aim of this assistance case is enabling a user to enter requirements, similar to a technical specification search in a data sheet, and find the appropriate component or adhesive. The search structure in the Knowledge Graph is similar to the structure of assistance case 1, shown in Figure 4. However, the search is done without the controlling instance and the *:hasProperties* relation is used to define the properties. Thus, there is a possibility to define properties such as the maximum or minimum application temperature. An assistance case associated extract of the Knowledge Graph is shown in Figure 6.

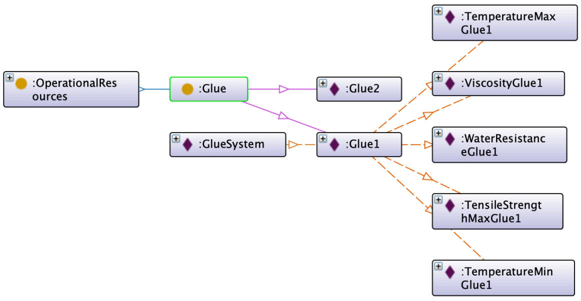


Figure 6: Adhesive selection based on system boundary conditions: Knowledge Graph extract

In this case, the data is stored for all values as well. The decision support starts with an extraction of the different adhesives. Then the *:hasProperties* data relation is used to extract associated properties. Decision support can then use algorithms, the Object relations, Data relations and the specified names to categorize and specify which types of properties are involved and assign them to a data grid. This data grid can output the appropriate component based on an input from the user in the frontend mask. The input mask can either be generated dynamically, based on the values, or defined in advance.

5.4 Further application possibilities

However, the two presented application possibilities do not describe the set of possible applications. In addition to these applications, for example, a temporal modeling of production processes based on the TIME ontology was designed. This can be used to optimize process times. Also a problem finding application, which is a flexible and easy to integrate ontology, was designed. In addition, OBDA mapping architectures for efficient data access have been developed and implemented. It can be seen that ontologies offer a wide range of use cases due to the possibility of complex modeling of semantic relationships and the integration of classical DBS via OBDA.

6. Summary and outlook

In this paper, a system for smart assistance in the reconfiguration of control processes was conceptualized and prototypically implemented on a use case of robot-based glass pane completion. The system is based on a Knowledge Graph built on presented common production ontology standards such as SUMO and CORA. In this graph, process-internal relevant information is consolidated, including the sequence of the process chain, information models and expert knowledge in the form of meta-information. Through targeted queries to the graph, knowledge can be gained about the programming of the process, which helps the end user when changing the process parameters. The system's mode of operation has been prototypically demonstrated in two examples: first, a parameter adjustment for adhesive change and second, adhesive selection based on system boundary conditions.

In further research, the aim is to use a learning or generally more intelligent data extraction algorithm to export knowledge in a more accessible way for the developer. This should be possible without requiring a detailed understanding of the respective Knowledge Graph, as currently necessary for SPARQL queries. In addition, optimization algorithms are to be tested that can make suggestions for process time optimisation from the generated Knowledge Graph. Furthermore, a subsequent study to survey experts from the industry should provide further possibilities to extend the functionality of the developed tool. Finally, the other components of the overall architecture described in Section 3 will be implemented, such as the connection to existing OPC UA models with an OPCUA2OWL algorithm.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2023 Internet of Production – 390621612.

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Biography

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