A Proposal for Ontology-based Integration of Heterogeneous Decision Support Systems for Structural Health Monitoring

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ABSTRACT
This contribution deals with an approach to ontology-based integration of Decision Support Systems for Structural Health Monitoring, specifically the implementation of a damage detection strategy for identifying and localizing damages to (civil) infrastructure (e.g., bridges, piping systems or wind turbines). Different institutions operate a large variety of systems for measurement planning, recording and analysis and each of these systems has its advantages and disadvantages depending, for instance, on the type of structure to be monitored. To combine the advantages of such heterogeneous systems, computer-supported collaboration is useful, which leads each institution to consider developing its own domain ontology. This knowledge can be integrated by means of a higher-level ontology to use different operations and approaches together for cumulative advantages. Hence, a concept for ontology-based integration building upon ideas of semantic data integration was developed, which stands out from other approaches as it uses a single ontology as its meta-vocabulary and a mediator-driven architecture.

Categories and Subject Descriptors
I.2.4 [Artificial Intelligence]: Knowledge Representation Formalisms and Methods – Semantic networks

General Terms
Management, Experimentation, Theory, Verification

Keywords
Decision Support System, Integration, Ontology, Structural Health Monitoring

1. INTRODUCTION
Structural Health Monitoring (SHM) can be seen as a method for identifying and localizing damages to structures or structural elements. Each structure has its individual dynamic behavior, which can be identified by analyzing the response of the monitored structure. Due to the fact that, in the area of SHM, individual institutions have developed several different systems for planning, recording, and analyzing measurements, an ontology-based integration of Decision Support Systems (DSS) for SHM is useful. Selecting an adequate system for measurement planning, recording and analysis depends, for instance, on the kind of measurement data or on the specified monitoring objectives.

Within the scope of the European Union project IRIS1, an integration ontology for DSSs in the field of SHM is to be developed and therefore described in this contribution. IRIS is a 3.5-year project (which started in October 2008) and involves 36 well known industrial partners and research institutions in different application areas (mainly SHM) world-wide. One of the main objectives of this research project is to develop an online risk management system to increase industrial safety in branches as the oil and mining industries or in the chemical and energy producing sectors of industry. To this end, intelligent assessment strategies for structural measurement data must be implemented. As mentioned above, the advantages of all possible systems for planning, recording, and analyzing measurements in different branches of industry can be combined to guarantee industrial safety and to reduce environmental pollution. Domain ontologies, which describe relevant information and knowledge of a certain domain, are very useful in this context. Matching these ontologies by means of a higher-level ontology will increase collaboration between different institutions and suggest the optimal systems for measurement assessment. Therefore an ontology-based integration approach will be introduced and described by explaining the

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1 Integrated European Industrial Risk Reduction System (IRIS), Funded under 7th FPW (Seventh Framework Programme), Research area: NMP-2007-3.1-3. see http://www.vce.at/iris/
structure of the ontology, the overall mediator-supported systems and their possible benefits for DSSs in the field of SHM.

Section 2 (Decision Support Systems for Structural Health Monitoring) describes the SHM-system BRIMOS® (Bridge Monitoring System), which was developed by VCE (Vienna Consulting Engineers). This SHM-system was devised specifically for the system domain – bridges – for measurement planning and recording, and its processes represent the basis for the system integration concept.

Section 3 (Integration Ontology and Related Work) presents theoretical background of ontologies in general and data integration as one typical application area. This theoretical background is important to distinguish between general ideas of (data) integration using ontologies on the one hand and the specific approach for SHM introduced in this contribution on the other hand.

Section 4 discusses the integration strategy for Structural Health Monitoring Systems in an automated and integrated manner, which should enable the desired integration of different heterogeneous Decision Support Systems.

Section 5 shows the approach of the ontology to the general process and decision support and gives concrete examples. The conclusion and intended future work are presented in section 6.

2. DECISION SUPPORT SYSTEMS FOR STRUCTURAL HEALTH MONITORING

The area of Structural Health Monitoring is an ambitious topic for current information- and knowledge-based systems, such as Decision Support Systems. In this section, BRIMOS® as a pioneer SHM-System will be discussed. The system description is based on processes and assessment methodologies shown in [24] and [25].

BRIMOS® can be defined as a method for system identification and damage detection, which is a passive decision support for SHM, in bridge structures due to its dynamic response to ambient excitation such as wind, traffic, and micro-seismic activity.

This Bridge Monitoring System has been used for many years in the field of SHM. The term SHM in the context of Ambient Vibration Monitoring comprises the recording of dynamic behavior using measuring instruments and the evaluation and analysis of the measured signals. The fundamental tools of health monitoring are system identification (SI), damage determination and localization, safety assessment, and maintenance management of the infrastructure.

The process itself starts with collecting meta data of a structure. These meta-data are used for detailed campaign planning, which can be divided into several steps (e.g., deciding whether detailed, periodic, or permanent measurements are to be conducted). At this stage a sensor layout is created and measurement schedules are written down.

After detailed campaign planning the monitoring takes place. Measured data are pre-processed depending on the type of data and usually written into a database before they are used for routine assessment (depends on the kind of measurement). Routine assessment provides, for instance, the modal parameters, namely the structure’s natural frequencies, its mode shapes, and its damping coefficients. These parameters, which are obtained from the measurements, represent the real condition of a structure. The measurements are, however, so precise that they can provide high-quality reference data for all future evaluation methods.

Routine assessment consists of any combination of assessment tasks, for instance, rapid frequency analysis, eigenfrequency analysis, drift calculation, analysis of trend cards, modal shapes, vibration intensities, energy leveling, etc. Describing any combination would go beyond the scope of the overall system description. Assessment results are used to update mathematical models of a structure. If previous measurement data and results are available, a simple comparison is possible. Otherwise the great number of partially similar structures already investigated supports Case-based Reasoning (CBR) processes.

The BRIMOS® process flow is the reference structure for this ontology-based approach. At this point it is important to define a general procedure module, which will be implemented as a mediator system to support the whole process during monitoring, computation and assessment to interact with end-users working with the different DSSs. This general concept is based on BRIMOS® and contains the steps shown in Figure 1. These process steps, alongside much semantic knowledge about the domain SHM and the specific DSS descriptions, are modeled within the integration ontology.

Using an ontology for integration purposes is one typical application of technologies within the Semantic Web, but its initial intention differs from the approach discussed in this paper. Therefore the following section discusses existing approaches in the field of ontology-based integration concerning workflows or the interaction of heterogeneous systems and applications.

3. INTEGRATION ONTOLOGY AND RELATED WORK

The term ontology has its origin in philosophy and metaphysics. It describes a branch of science that deals with the nature of being and focuses on questions concerning the existence of concrete things and their relationships [4]. For computer scientists, however an ontology is an "explicit and formal specification of a shared conceptualization of a domain of interest [12]". One major advantage of ontologies can be seen in the aspect of working with peripheral web resources, which are distributed but accessible within the so-called Web of Data. Developing a system that interconnects with semantically different platforms, frameworks, agents, etc., and their resources requires, a mechanism which assures valid syntax and semantics to achieve interoperability. Davenport and Prusak called this explicit, distributed and accessible resource a common vocabulary: "People can’t share knowledge, if they don’t speak a common language [8]". This definition can be extended by replacing the word people with agents. Hence, ontologies can be seen as knowledge bases which enable interconnectivity between different agents, be they humans or computers. This is one of the most
important application areas of ontologies. Furthermore ontologies can be used to search for semantically annotated documents, to conduct queries within these information resources, they can be employed for data integration and to provide proper interconnectivity between different and heterogeneous systems, to search and compose (web) services, etc. This contribution first discusses key concepts in this area and the original idea of using ontologies for combining heterogeneous systems, and then focuses on the application of semantic (data) integration.

Data integration, as an important concept in information systems, is connected strongly to the architecture of federated databases and to its aspects of combining distributed, autonomous, and heterogeneous schemas [2]. These concepts characterize the main idea of federation alongside design autonomy, communication and execution autonomy [18][20], network characteristics of distributed agents, and heterogeneity concerning structure, syntax, system and semantics [5][7]. These properties of data integration can also be found in areas such as application integration and application interoperability [2]. The DSS data integration ontology (see section 4) is a global conceptualization that provides meta information about systems and supports a mediator component to maintain the whole routine by deciding which step comes next and what are possible applications to work with a certain output (see general workflow in section 2 and also section 4). Global conceptualization was one of the first application areas (first mentioned by Gruber [12]) for ontologies. The overall concept of ontology-based data integration is based on this initial idea and will be defined as discussed in [6]: “We call semantic data integration the process of using a conceptual representation of the data and of their relationships to eliminate possible heterogeneities”. The problems of possible heterogeneities within this approach will be managed by the integration ontology, which has to guarantee full semantic support for every supported DSS. Hence, an ontology for (data) integration can also be used for metadata representation, to support high-level queries, for declarative mediation, and for mapping support [6].

The definitions and descriptions discussed in the previous paragraphs deal with the general idea of (semantic) data integration. Below, we describe the concepts that are mainly used in this research area and whether they are appropriate for DSS data integration. The most frequently referenced and explained approaches are general concepts that deal with different data sources, ontologies, and mappings between them. Depending on the frame of reference, these concepts are termed local-as-view (LAV), global-as-view (GAV), or – in case they are combined – global-local-as-view (GLAV) [6][18]. These approaches focus mainly on the integration of distributed and separated ontologies, but the topic of integration is broader than just the matching, aligning, or merging of such different semantic networks by using mapping conditions. In [22], the authors deal with different application areas for ontology-based integration issues, such as the building of ontologies based on pre-existing models or the general use of ontologies in applications. Integration also differs between different comparing systems and approaches such as ONIONS [10], Ontolingua Server (Farquhar), and PhysSys (Borst), which are also described in [22]. The various descriptions and explanations of the term integration are ambiguous and differ from approach to approach. However, these differences will not be discussed in this paper. For the purposes of this paper, “ontology-based data integration” in the area of Decision Support Systems for Structural Health Monitoring will be defined as follows:

**Definition.** An Integration model for DSS in SHM (I) is defined as a set of systems (S) which contains knowledge about the type of needed parameters (see section 5 for examples) and process steps (P), which are mapped (together) by matching their inputs (In) and outputs (Out) such that for each described system there is at least one adequate process step; otherwise the system description is not appropriate (inappropriate systems will be handled as semantically invalid). Therefore the following constraint must be satisfied by the ontology for integrating heterogeneous DSS:

\[ \forall_{s \in S} \exists p \in P \exists_{in \in In} \exists_{out \in Out} (p.i = x.i \land p.o = x.o) \]  

(integrity constraint)

Furthermore, o and i are only semantic descriptions of outputs and inputs provided by a certain system and needed by specific process steps. The DSS integration approach classifies systems based on the constraint above by matching their inputs and outputs and therefore classifying a system or not (see section 5 and table 3).

The roles of ontologies in integration are manifold as described in [22] and [23]. In [23], a comparison of different approaches in this scientific area can be found. Several information integration systems, such as SIMS, OBSERVER, DOME, COIN, Carnot, InfoSleuth, KRAFT and others are mentioned that focus on the use of ontologies for integration purposes. These systems are classified in [23] according to the role of ontologies (content exploitation – single, multiple ontologies, or a hybrid approach; ontology representation such as description logics, frame-based systems or object languages; the use of mappings between integrated ontologies and the relevance within ontological engineering). It is not the intention of this paper to give an overview of these approaches (they already are well described in [23]), but it must be clarified whether these approaches are suitable for the integration of heterogeneous decision support systems into a well-defined workflow. The following fundamental ideas of some representative approaches can be found in [3]:

- **Carnot:** This system has the goal of addressing the problem of logically unifying physically distributed, heterogeneous information.
- **COIN (Context Interchange):** Semantic Interoperability among heterogeneous information sources.
- **DOME (Domain Ontology Management Environment):** It is focused on ontology development by using software reverse engineering techniques.
- **InfoSleuth:** An extension of Carnot to make legacy database systems easily accessible via Web.
- **KRAFT (Knowledge Reuse And Fusion/Transformation):** Primarily conceived to support configuration design of applications among multiple organizations with heterogeneous knowledge and data models.
- **OBSERVER (Ontology Based System Enhanced with Relationship for Vocabulary hEtogeneity Resolution):** An approach that proposes managing multiple information sources through ontologies.
- **SIMS (Search in Multiple Sources):** The System essentially provides access and integration to multiple sources of information.”
Considering these slightly described approaches, it can be identified that typical data or information integration systems and concepts are located in the field of integrating information and data described in ontologies or to use those semantic networks to combine different information sources. Those conceptualizations do not fully comply with the idea of the DSS data integration approach described in this paper, because the built ontology should not help to combine different data sources, but it should enhance the collaborative use of heterogeneous Decision Support System based on a predefined general workflow. Furthermore, typical integration approaches sometimes do not only include the use or integration of an ontology, they are more or less a set of concepts, which also describe the benefit for developing an ontology, e.g. KRAFT or SIMS. This is also not intended by the integration ontology of this contribution. Nevertheless, the general aspects of integration approaches described in [23] should be taken into account and discussed with the DSS approach.

The role of ontologies within an integration task is important, especially to define “the representation formalism of an ontology” [23]. In contradiction to this question, the integration ontology (see section 4) can be classified as a single ontology approach as described in [23] and [3], similar to SIMS. Therefore, the necessary knowledge for the combination and classification of certain systems is described within this ontology. Another suitable aspect is the ontology representation. The integration approach uses OWL DL and its description logic SWOOF to describe the systems and the general workflow, because of its expressivity and support for proper reasoning. Furthermore, it is not fixed, whether to use a special OWL profile like OWL QL or OWL EL instead or to enhance the knowledge representation with rule language concepts concerning RIF (Rule Interchange Format) [15]. The current progress of implementation fixed the use of OWL as an ontology language, but the concrete “sub-language” maybe changes. The remaining aspects of [23] concerning the use of mappings and the relevance for ontological engineering cannot be handled within this approach.

Nonetheless, it can be concluded, that current concepts and systems in this scientific area often focus on the integration of several sources and schemas, but, as described above, the key issue of this approach is the integration of the system itself. Therefore, it is more a topic concerning ontology-based workflows and the semantic description of DSS operations in the area of Structural Health Monitoring.

The semantic description of processes and especially of business processes is strongly connected with Semantic Web Services, which also intend to build up an interaction path between several services or describe them in a way to use those semantics for improved search and composition of services. Those approaches described in [16], [14] and [1] are too complex for the integration approach and not appropriate, because the initial idea for classifying an system as executable for a specific process step (see section 4 and 5) only needs inputs and outputs. Therefore, this approach matches the definitions of section 6 in [17], which describes several scenarios concerning the semantic equivalence of two services. This approach could be matched with the task to classify systems as adequate for a certain process step (see integrity constraint), by comparing their input and outputs but currently not more (see section 6 for future work concerning the use of rule languages and ontology improvements).

The mentioned methodologies are typical for data integration systems, where two or more sources with different schemas have to be merged in a syntactical as well as a semantically manner. The conceptualization of an ontology for heterogeneous DSSs, as already mentioned above, differs from this point of view. Furthermore, the introduced architecture combined with an specific interaction concept and the integration ontology itself will be described and drafted in the next section.

4. INTEGRATION ONTOLOGY FOR STRUCTURAL HEALTH MONITORING

In the field of Structural Health Monitoring many institutions operate a large variety of systems for measurement planning, recording and analysis. As a sophisticated representative BRIMOS® was described in section 2. An outlier detection approach [21] and a case-based system [9] can be mentioned in addition. Each of these individual systems has its advantages and disadvantages, mainly depending on certain circumstances of an application, like the type of a regarded structure, the kind of measurement data, defined monitoring objectives, etc. With the intention to increase precision and reliability of SHM processes in general, it is useful to combine the advantages of these individual systems.

Besides further developing sensors, recorders and measurement analysis systems within the EU project IRIS, partners identified collaboration as an important key factor of success. On behalf of that, a concept for computer supported collaboration by means of semantic technologies was worked out. The following Figure 2 shall illustrate this idea.

Figure 2. System Landscape

There is a certain number of institutions (civil engineers), called Group in the Figure 2 above, which since years collected many gigabytes of measuring data and other documents related to SHM. To increase the accessibility of these information sources, each participating institution develops its own domain ontology. Furthermore, the participants' knowledge can be integrated by mapping the domain ontologies by means of a higher level ontology (here called IRIS Ontology). A web-based system should make the accumulated information easily accessible to the cooperation partners in the form of a knowledge base. However, this knowledge base is not the main focus of this contribution, but rather another aspect besides sharing knowledge. Figure 3 picks out the relevant parts from the system landscape to clarify the main concern of this contribution.
In addition to support knowledge interchange between involved institutions, their systems for planning, running and analyzing measurements should be made available for each other in an automated and integrated manner. Hence, a concept for an ontology-based integration of DSSs for SHM was developed, as presented in Figure 3. An Integration Ontology, which is based on the certain Domain Ontology and also uses the IRIS Ontology for referring to relevant background information serves a mediator system: The integration process should be provided by the mediator instance, which classifies certain inputs at runtime by reasoning the ontology and extracting the computed individuals and their class assertions. This founded information will be used to decide whether the current process step should be repeated, return to the previous one or proceed to the next step. The decisions and operations of the whole system area should not be hardcoded and maintained by an algorithm, the knowledge about the supported and available systems for each process step should be independent available. The mediator system can be seen as a kind of router, which delegates a user through the measuring and analysis process for suggesting the appropriate tooling at the right point of time. To make this possible, the mediator system has to be aware of the general workflow shown in Figure 1, which covers a whole measuring campaign on a certain level of abstraction. This described workflow is abstract enough to make the process suitable to a large variety of applicable DSSs that can be used together for better decision support.

![Figure 3. Integrated Decision Support Systems](image)

**Figure 3. Integrated Decision Support Systems**

At each step, DataPreparation for instance, the mediator should be able to suggest suitable systems to a user and, with the help of an appropriate learning component, the most popular system for a certain process step could be provided. In the course of that, the ability can be gained to generate combined solutions for certain problems, which can rely on the contribution of a certain number of participating systems, making results more reliable and hopefully increasing the overall quality of a measuring campaign. Furthermore, individual DSSs can profit from each other. A case-based system for instance could import input and corresponding output of other systems and generate new cases to extend its case base, which can increase future problem solving capabilities. In recapitulatory terms, the main objective of integrating individual systems to increase the quality of SHM in general by reaching highly reliable results at each process step of a monitoring campaign.

The Figure 4 above gives an overview of the most important classes of the Integration Ontology, which describes the semantics concerning the needed input and output parameter of each process step concerning the general workflow introduced in section 2 and the description of certain systems that provide several features to assimilate and to compute specific output parameters. The ontology was developed by using Protégé (version 4.0.2) and consists of 830 RDF statements, which derive from 62 classes, 37 object properties, 41 data properties and currently 52 individuals and their axioms. The TBox and ABox are not finished and will be enhanced in the future. Therefore it is currently not possible to clarify the complexity of the ontology and the performance of the whole proposal, but it is one of the major tasks to be declared in the future work (see section 6). As an outlook of section 5 in combination with the description of a process step (see table 1 in section 3), DSS will be classified as suitable for a certain step or not (see classification results in table 4) by using the tableau algorithm of the pellet reasoner, which is mainly used for reasoning tasks within this approach. These descriptions are the key concepts of the ontology and represent the general workflow and its semantics discussed in section 2.

The nodes (classes) System, ProcessStep, CampaignPlanning, Monitoring, DataPreparation and Assessment from Figure 4 are of main interest for the system integration concept. The class System represents available DSSs, a case-based system for instance, while the class ProcessStep realizes a representation of the individual steps of a monitoring campaign, which are campaign planning, monitoring, data preparation and assessment.

In contradiction to the level of heterogeneity, which is important for the degree of detailed information concerning the system input and output, it is an intended goal of this approach to achieve whether DSS in the area of SHM are easy and fast to integrate and compute an overall benefit for decision making or not. Furthermore the presented ontology is not the final version; it is a proposal that will be enhanced through deeper domain knowledge.
especially the concrete format and type of parameters and their representation. Nonetheless it is clear that the heterogeneity of those systems influences the classes and properties within the ontology, which has to be handled through improvements of the current approach (see future work).

The introduced concept of an Integration Ontology will be described by discussing typical system descriptions, their classification and validation in the following section.

5. ONTOLOGY-BASED INTEGRATION OF DSS FOR SHM

The ontology describing the process flow discussed in section 2 and the system descriptions of the heterogeneous Decision Support Systems shown in Figure 2 will be mentioned in this section by focusing on the classes System and ProcessStep.

The initial idea of using an ontology for integration issues is based on the possibility of reasoning and classifying. These features are important for the mediator component, which schedules the whole process. This component uses the ontology for identifying available systems that support certain process steps. Each step and system is described within the ontology and after classification every system contains, based on the semantic enrichment and property assertions, one or more class assertions, which identifies a system whether as a candidate for a certain process step or not. The following description logic statements in Manchester OWL syntax are examples for typical system descriptions:

<table>
<thead>
<tr>
<th>Individual</th>
<th>RBR_1</th>
<th>Types: System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facts:</td>
<td>hasInput Measure, hasInput ModalParameter, hasOutput AssessmentResult</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual</th>
<th>BRIMOS®</th>
<th>Types: System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facts:</td>
<td>hasInput MetaData, hasInput ConfigData, hasInput Campaign, hasInput Measure, hasInput ModalParameter, hasOutput Measure, hasOutput ModalParameter, hasOutput AssessmentResult</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual</th>
<th>CBR_JKU</th>
<th>Types: System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facts:</td>
<td>hasInput Measure, hasInput ModalParameter, hasOutput AssessmentResult</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Example for System Descriptions

Each of these system descriptions contain the possible input and output parameter, which are necessary for computing results like measures after monitoring or a concrete assessment like a risk level or damage information.

The systems will be classified during the reasoning as individuals of one or more process step classes. Process steps are described similarly to systems:

<table>
<thead>
<tr>
<th>Class: CampaignPlanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubClassOf: ProcessStep</td>
</tr>
<tr>
<td>EquivalentTo: System</td>
</tr>
<tr>
<td>and hasInput some (MetaData, ConfigData) and hasOutput some (Campaign)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class: Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubClassOf: ProcessStep</td>
</tr>
<tr>
<td>EquivalentTo: System</td>
</tr>
<tr>
<td>and hasInput some (Campaign) and hasOutput some (Measure)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class: DataPreparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubClassOf: ProcessStep</td>
</tr>
<tr>
<td>EquivalentTo: System</td>
</tr>
<tr>
<td>and hasInput some (Measure) and hasOutput some (ModalParameter)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class: Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SubClassOf: ProcessStep</td>
</tr>
<tr>
<td>EquivalentTo: System</td>
</tr>
<tr>
<td>and hasInput some (ModalParameter) and hasOutput some (Assessment)</td>
</tr>
</tbody>
</table>

These process steps and the examples above for system descriptions are matched together and after a reasoning process the systems are classified as following (only class assertions):

Table 2. Process Step Definitions

<table>
<thead>
<tr>
<th>Individual</th>
<th>BRIMOS®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types:</td>
<td>CampaignPlanning, Monitoring, DataPreparation, Assessment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual</th>
<th>CBR_JKU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types:</td>
<td>Assessment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual</th>
<th>RBR_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types:</td>
<td>Monitoring, DataPreparation</td>
</tr>
</tbody>
</table>

After this classification the ontology is ready for the mediator component that uses the inferred ontology model and SPARQL as query language for identifying available systems. The DSSs are black boxes. Hence, the mediator component knows nothing about these systems and has to search within the ontology for appropriate systems, which can work with certain input

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2 Example for a rule-based reasoning system

3 This system is a concept of Case-based Reasoning for Structural Health Monitoring and is proved and implemented by members of the Institute for Applied Knowledge Processing at the Johannes Kepler University Linz (for more information see [9]).
parameters as well as computing an appropriate output. It has to be mentioned that the ontology only contains knowledge for supporting the mediator within these phases, so it is necessary to consider that concrete localization and communication with the systems is not part of this meta-vocabulary. The mediator is only a scheduler, which maintains each process steps, searches for available systems, interacts with the DSS during sending and retrieving input and output parameters and communicates with the end-user, who reviews the results of the DSS and interacts with the overall system. The end-user is able to navigate through the whole process and to tell the mediator whether a certain result is accepted or refused. Concerning this assessment of adequacy for a certain system the respective individual within the ontology will be modified in such a way that it gets a property assertion hasQuality, which tells the mediator an appraisal of quality for the system and the concerned process step.

**Example.** Consider the mediator retrieves computed measures from BRIMOS®, which are evaluated by a technician. During evaluation the technician classifies these results as inadequate or wants to see an alternative result before s/he proceeds to the next step. This decision takes place in the ontology by modifying the properties of the system quality for a certain process. If a system computes good results and is accepted by the end-user, the acceptance count (hasAcceptCount of quality individual) will be increased. Otherwise the count of refused results (hasRefuseCount) will be enhanced. After this back tracking to the results of the previous process step CampaignPlanning the BRIMOS® individual maybe comes with following assertions:

<table>
<thead>
<tr>
<th>Individual: BRIMOS®</th>
<th>Types: CampaignPlanning, Monitoring, DataPreparation, Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facts:</strong></td>
<td>hasInput MetaData, hasInput ConfigData, hasInput Campaign, hasInput Measure, hasInput ModalParameter, hasOutput Measure, hasOutput ModalParameter, hasOutput AssessmentResult, hasQuality Q_Bri_Monitor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual: MonitorDummy</th>
<th>Types: Monitoring</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Individual: Q_Bri_Monitor</th>
<th>Types: Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facts:</strong></td>
<td>hasProcessStep MonitorDummy, hasAcceptCount 10, hasRefuseCount 1</td>
</tr>
</tbody>
</table>

This validation of certain systems provides helpful information about the quality of system outputs and its adequacy. So it is possible not only to identify available systems but also to be implemented that only systems of a certain acceptance rate should be suggested to the end-user. Furthermore this rate can be adjusted for each end-user individually. This feature makes it possible to enhance the pure classification of the ontology and provides qualified suggestions for systems. This means that the ontology learns whether a system is good for a certain process step or not. The most important associations of the DSS approach are shown in Figure 5 concerning process steps and systems:

![Figure 5. Associations between ProcessStep and System](image)

During the whole process the mediator constantly works with the ontology, because after every retrieve of an output it has to decide which system should be applied next. Finally, every process step monitored by the mediator contains four phases: search, decision, interacting, and validation. During searching the system determines available and adequate DSSs for the current progress. The decision, which proposed system will be used, has to be done by the end-user. Within the interacting phase the mediator communicates with the respective computer agent till results can be presented. At the end the validation phase does the evaluation of the system based on the user acceptance as described above.

**6. CONCLUSION AND FUTURE WORK**

This paper describes an approach for integration of Decision Support Systems in the area of Structural Health Monitoring.

The used and discussed integration ontology consists of descriptions from process steps and DSSs, which are classified as candidates for certain tasks. The mediator component, which implements all communication and interaction processes that are needed for interacting with the systems and with the end-user, searches the inferred ontology for appropriate systems for certain input parameters. These systems are suggested to the end-user who decides which system will be executed next. After computation, the results are evaluated by the end-user and concerning this decision the mediator either increases the acceptance count for the system within the actual process step, takes the output and searches for systems which work with these parameters or the previous process step will be repeated and the system’s refuse count will be increased. The process flow is finished if the end-user accepts the last result during the assessment or the whole process is cancelled causes of inadequate decision support or other reasons depending on the output quality.

Since many SHM systems are in an experimental state or enhanced continuously, the described approach can be seen as a possibility to obtain a powerful testing and evaluation environment. Integrated SHM approach promises results with a potential of a high reliability level, which might increase safety at large. Hence, practical evaluation of the whole approach must be clarified.
The authors believe that expressivity of the integration ontology can be enhanced by adding rules, in particular production rules, to the knowledge base. This enhanced approach will use RIF PRD (Rule Interchange Format Production Rule Dialect) to bridge the gap between OWL and horn logic based rules. The RIF provides a universal interchange format for interoperability of different rule languages by developing dialects for inductive, deductive, and reactive approaches [19] and a framework for modeling RIF-rules. Important features are the syntax and semantic data model as well as the signature concept: "Signatures determine which terms and formulas are well-formed [15]."

Furthermore, it is important to prove whether this ontology-based integration approach (i) considers sufficient domain knowledge, (ii) delivers easy, intuitive and powerful decision support and (iii) provides flexible process steps, so one can step back and compare different DSS results in the area of Structural Health Monitoring.

7. REFERENCES


