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An Ontology-Based and Service-Oriented Information System Architecture to Enable Sustainable Management of Scarce Non-Renewable Resources

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An Ontology-Based and Service-Oriented Information System Architecture to Enable Sustainable Management of Scarce Non-Renewable Resources

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ABSTRACT

The scarcity of non-renewable resources today is a more and more crucial issue for many branches of industry. To counteract these problems, extensive, timely and up-to-date information on non-renewable resources' supply and demand is essential. Nevertheless, this information today is distributed, heterogeneous and only available in an informal or semi-formal structure. Thus, companies often do not have the right or up-to-date information to manage their usage of non-renewable resources adequately. This paper investigates if an ontology-based service-oriented information system architecture can cope with these difficulties and thus form the basis for the sustainable management of non-renewable resources. Based on an overview of the therefore needed types of information, an architecture that enables collection, structuring and processing information on non-renewable resources is presented. A prototypical proof-of-concept implementation illustrates its benefits and its general applicability. Finally, the architecture is evaluated conceptually and by use of the Architecture Tradeoff Analysis Method.

Keywords (Required)

Non-renewable resources, raw materials, commodities, ontologies, SOA, information system architecture, ATAM.

1. INTRODUCTION AND MOTIVATION

Today, high-tech products contain an ever increasing number of non-renewable resources. Nowadays even a standard cell phone contains 40 different elements, most of them in minimal amounts of only some milligrams (Reller, Bublies, Staudinger, Oswald, Meißner and Allen, 2009; Hagelüken and Meskers, 2008). This makes producing companies extremely vulnerable to resource shortages, as already the absence of one out of these 40 different elements renders production impossible. Even if there are substitutes, a time-consuming readjustment of fabrication will be needed. Besides the mere availability of a resource, its price can heavily affect a company's earnings: For example the prices of copper have nearly tripled since early 2009 (see Figure 1). Thus, the usage of non-renewable resources involves high risks of production downtimes and loss of profit and hence necessitates large efforts to manage the usage of non-renewable resources.

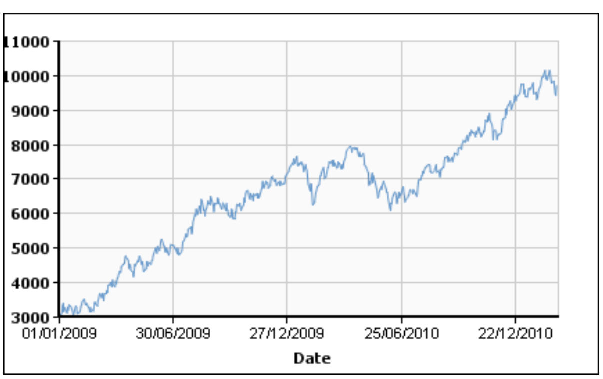

Figure 1: Copper prices since 2009 (source: London Metal Exchange)

Nevertheless, most resources are sufficiently available from a geological point of view. The main problem is that it takes about five to ten years to increase mining production by opening up a new mine (Hartman and Mutmansky, 2002), while on the other hand the demand for non-renewable resources shows many short-term fluctuations: For example the U.S. imports of gallium have nearly doubled from 2009 to 2010 (U.S. Geological Survey, 2011). This term transformation entails a large risk of supply gaps and price fluctuations, making provident risk management of long-term availability essential. To plan, organize and control the use of non-renewable resources, a broad range of information regarding prices, demand and supply is needed. Nevertheless, this information today is only available in a scattered way and stored in informal or semi-formal file formats, making the automated integration in decision-support systems virtually impossible with current architectures.

Thus, this paper analyzes if an ontology-based and service oriented information system architecture can improve the capability to efficiently manage non-renewable resources. While this section outlines the economical problems of non-renewable resources, section 2 illustrates what information is needed to make decisions on the use of non-renewable resources and derives the core requirements for an information system architecture to integrate and structure this information. Section 3 thereupon introduces the utilized technologies, i. e. ontologies and service-oriented architecture. If ontology-based architectures can really meet the requirements to sustainably manage non-renewable resources is analyzed in section 4 by constructing and prototypically implementing an exemplary architecture. Section 5 presents a conceptual evaluation, while section 6 performs a scenario-based evaluation using the Architecture Tradeoff Analysis Method.

2. INFORMATION NEEDS AND SYSTEM REQUIREMENTS

To make economical and long-term reasonable decisions regarding the use of non-renewable resources, a large and many-sided amount of information is required.

Here, the **supply** with non-renewable resources is a core subject. The domain of raw materials' mining is a wide and complex area and necessitates extensive familiarization. For instance, while reserves stand for deposits that are technically and economically exploitable, resources name deposits that are technically, but not yet economically exploitable (U.S. Geological Survey, 2011). In addition, factors like extraction costs per ton of material, exploration of new deposits or their ore quality have to be considered (Krautkraemer, 1998). This information usually is collected from mining companies and aggregated by geological agencies like the USGS (U.S. Geological Survey, www.usgs.gov) or the German BGR (Federal Institute for Geosciences and Natural Resources, www.bgr.bund.de). Furthermore, specialized companies like the Swedish Raw Materials Group (www.rmg.se) offer commercial access to a large number of mining related facts. Without this information, companies have no solid basis to predict future availability and potential shortages.

In contrast to this area, the raw materials' **demand** at first sight seems to be rather straightforward: By means of parts lists, production plans and order books companies can largely foresee their future demand – at least on the short and medium term. However, the demand for non-renewable resources is influenced by every new product, every single producing company and every single customer. As a result, the demand for non-renewable resources is a very complex system. All in all, an accurate prediction of the demand for non-renewable resources seems to be impossible, while, on the other hand, long-term trends and scenario-based prognoses (European Commission, 2010) can help decision-makers to prepare for possible future developments. Thus, different kinds of predictions are needed for long-term decision-making. This information usually is derived from scientific surveys (European Commission, 2010), forecast institutions or case studies offered by consultancies.

Figure 2: Tin prices since 2006 (source: London Metal Exchange

Thirdly, several specific **market effects** influence the development of the prices and availability of non-renewable resources. Here, the rate of interest (i.e. from www.ecb.int or www.federalreserve.gov) is of central importance, as it determines the amount and time pattern of investments and is also connected with inflation. These figures are usually provided by national banks or specialized financial service providers. In addition, the market structure determines the pricing, e.g. within an oligopoly. This information might be provided by inter-trade organizations, governmental or geological agencies, for instance in the case of platinum, where 77% of the world-wide production comes from South-Africa (European Commission, 2010). Lastly, speculation highly influences current and future prices. Thus, the information on factors like stock-keeping or prices of future transactions is highly helpful for companies to avoid negative effects on earnings. Data on these factors as well as time series on past and current prices and futures can partially be acquired from stock exchanges (i.e. www.lme.com).

Finally, there is a number of **external factors** that influence the demand, supply and price of non-renewable resources. For example, the ban of lead in electronic products by the European Union in 2006 (Directive 2002/95/EG) has significantly lowered the lead prices while, on the same time, it has heavily increased prices of the substitute, tin (see Figure 2). While future laws and regulations such as export quotas are generally hard to predict, they are usually enacted within a transitional period that enables companies to implement a smooth adjustment. Thus, information on future coming into effect of laws and regulations is important for producing companies, while making it necessary to procure information from law offices or directly from public bodies.

In summary, the overall information needs can be classified as seen in table 1:

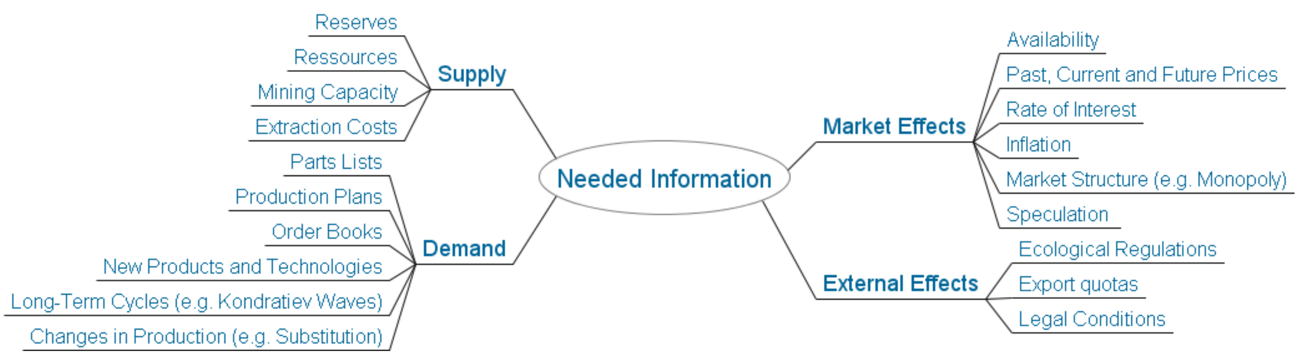

Table 1: An overview of needed information to sustainably manage non-renewable resources

All in all, the information needed for the sustainable management of non-renewable resources comes from at least a dozen of different stakeholders and providers, thus making manual exchange of information virtually impossible and uneconomical in most cases. Therefore, automated information exchange and decision-support building thereupon by means of an information system is inevitable. Such systems are required to cope with (a) **heterogeneous** and (b) broadly **distributed information sources**. As there is a vast number of stakeholders with varying requirements, the information has to be stored in a (c) **decentralized** way allowing (d) **modular composition** of different components. In addition, the ability to (e) **dynamically integrate constantly changing information** is of essence, thus requiring (f) **formalized information structures** enabling **automated information processing**. At last, to minimize entry obstacles and to encourage a substantial participation of small and medium enterprises, (g) **open standards and architectures** are preferable. Altogether, these requirements can be summarized under the fundamental aim of (h) **interoperability**. While there might of course be a number of additional company-specific requirements, the requirements mentioned above represent the core requirements concerning the design of an information system architecture to enable and improve the management of non-renewable resources.

The **main research question** of this paper is therefore: Is an ontology-based and service-oriented information system architecture able to improve the management of non-renewable resources and how can such an information system architecture be constructed?

3. FUNDAMENTALS OF ONTOLOGIES AND SERVICE-ORIENTED ARCHITECTURE

Guarino et al. describe ontologies as "means to formally model the structure of a system"(Guarino, Oberle and Staab, 2009). An ontology is a knowledge database consisting of formally defined concepts and their relations as well as individuals representing their instances. Ontologies were first introduced as "explicit specification of a conceptualization" (Gruber, 1993) and are used to structure and store information. An ontology e.g. could contain the concepts "Product" and "RawMaterial", the relation "requiresRawMaterial" and the individuals "TV Screen" and "Indium", associated with an instance of "requiresRawMaterial". Ontologies themselves are usually stored using the Web Ontology Language (OWL, www.w3.org/TR/owl2-overview). From other means of information storage like relational databases ontologies differ by three characteristics: (i) they enable agreement on the meaning of specific terms and thus facilitate information integration, (ii) they are specified in a formalized logical language and thus are unambiguous and (iii) they come with executable calculi enabling automated querying and reasoning (Oberle, 2005).

The formal language family used to specify the information contained in ontologies is called "Description Logics". Description Logics are basically a decidable two-variable fragment of first-order predicate logic (Sattler, Baader and Horrocks, 2009). A common sublanguage of Description Logics is SROIQ, that is used in OWL 2 (Horrocks, Kutz and Sattler, 2006). As this language is decidable by means of reasoning algorithms, the consistency of an ontology can be determined automatically. In addition, queries can automatically be answered by testing the consistency of the union of the ontology and the query taken as statement. In practice, this task is carried out by specialized reasoning libraries like pellet (pellet.owldl.org) or HermiT (www.hermit-reasoner.com).

Although ontologies and reasoning are still an intricate technique requiring extensive familiarization, they are increasingly used in practical application. One important field of application is knowledge management. Here, ontologies can support knowledge search, retrieval and personalization and serve as the basis for information gathering, integration and organization (Abecker and van Elst, 2009). In the area of information systems, ontologies are used e.g. for information modeling (Ahleman and Teuteberg, 2007), for automated model transformations (Roser and Bauer, 2006) or as basis for decision support systems (Chen, 2010).

With service-oriented architecture (SOA), on the other hand, "technical and philosophical disparities are blanketed by layers of abstraction that introduce a globally accepted standard for representing logic and information" (Erl, 2005). SOA enables interoperability and architectural composability and is based on web services. A web service encapsulates some specific functionality and is accessible through a service provider. Thereby, semantic SOA strives to advance the world wide web to a repository of semantically annotated services enabling automated interaction and algorithmic reasoning (McIlraith, Son and Zeng, 2005). Semantic web services can provide reliable service composition by formal input and output definitions (Mahmoud, Dovenmühle and Gómez 2009). Thus, semantic SOA provides means for a modular and automated combination of different information systems.

4. AN ONTOLOGY-BASED SERVICE-ORIENTED ARCHITECTURE FOR SUSTAINABLE MANAGEMENT OF NON-RENEWABLE RESOURCES

This section describes the proposed architecture to improve the sustainable management of non-renewable resources, mostly being based upon two architectural approaches: ontologies and SOA.

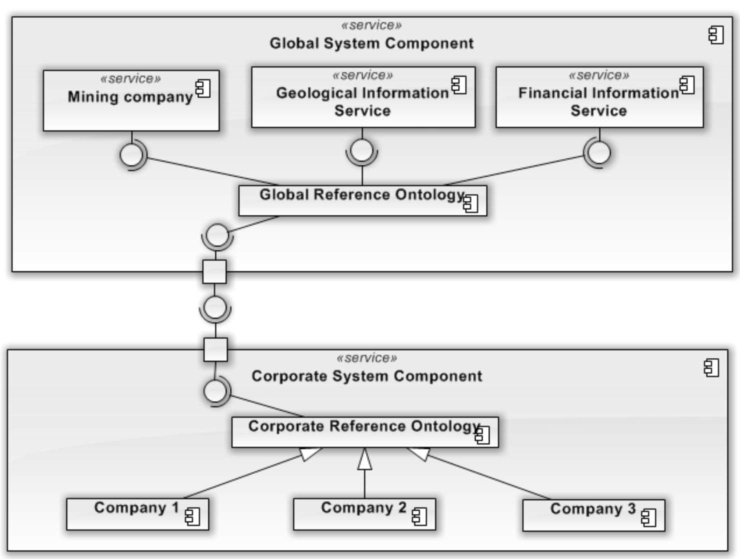

Figure 3: The overall information system architecture

Overall Architectural Structure

Figure 3 shows the overall structure of the proposed architecture. The system is composed of two basic components: The global and the corporate system component. While the first has the role of an information provider and thus is designed as service, the latter primarily acts as information consumer. In the global system component, the global reference ontology accesses a number of primary information providers and aggregates their output to provide it as service for the corporate system component. Therefore, the primary information providers themselves are service-providers for the global reference ontology. In the corporate system component, only the whole component itself acts as a service, offering companies access to global and corporate information that corresponds to the global or corporate reference ontology. Thus, the information flow strictly follows a top-down pattern, while each lower component can add new and more specific information.

In practice, the corporate system component will in most cases be an extension of the enterprise resource planing system of one or more companies, i.e. being part of a holding. The global system component provides company-independent data and thus can be made available by the company itself or by some kind of service provider, i.e. a geological government agency or a specialized external company.

The Architectural Approach of Ontologies and Reasoning

As described in section 3, ontologies enable the formal specification of the semantics of entities. Thus, they can contribute to an improved aggregation of heterogeneous information. Figure 4 shows a short example of an ontology that can combine different classifications of deposits.

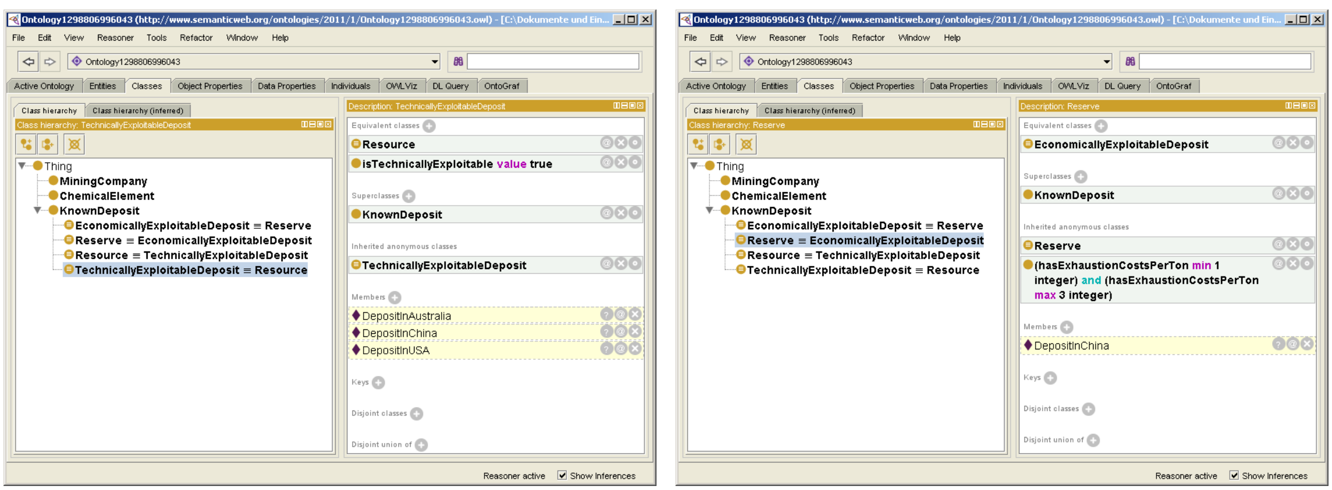

Figure 4: An example of the global reference ontology in development using the tool protégé (protege.stanford.edu)

This ontology amongst others tackles a common problem: the confusion of reserves and resources. To solve this problem, a formal definition of reserves and resources is given, based on technically and economically exploitable deposits: All deposits that are technically exploitable are considered as resources (in this case the deposits in Australia, China and the US), while the only economically exploitable deposit in China is considered as reserve. This definition does not only counteract confusion, but also enables automated translation between different information sources using different concepts like reserve/resource or technical/economical exploitability. Of course, this example only shows a fraction of possible features realized by an ontology. Therefore, figure 5 shows an extended excerpt of the ontology for non-renewable resources. For reasons of presentation, concepts from both the global and the corporate components are integrated into one ontology, divided in two distinct branches however. Even with this limited ontology, decision-support is possible, e.g. by identifying critical resources, through calculating which chemical elements are critical in terms of availability. Thus, the presented architecture significantly improves the possibilities of the integration and processing of heterogeneous information.

Nevertheless, this approach requires the relevant information needed for reasoning tasks to be stored in one or more ontologies at hand. At best, all these ontologies are globally accessible by an Uniform Resource Locator (URL). However, this is not the case yet, what necessitates SOA as an additional architectural approach to aggregate distributed information into one or more ontologies that are able to communicate with each other.

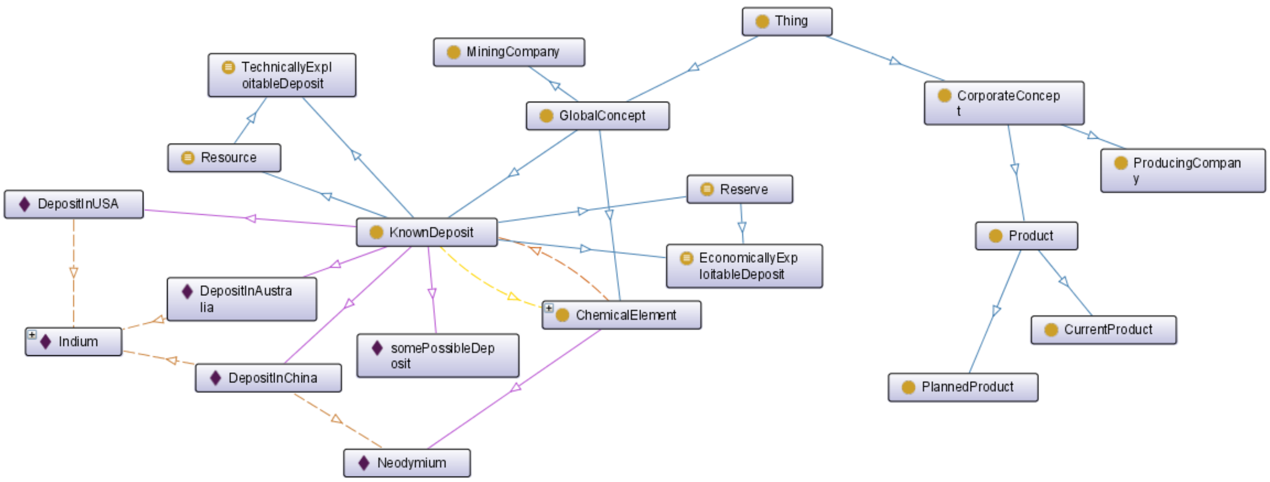

Figure 5: An exemplary excerpt of the proposed reference ontologies

The Architectural Approach of Semantic SOA

The presented ontology-based architecture is now to be extended by a service-oriented approach. The core feature of SOA is to enable composability by partitioning a system in self-contained building blocks that each serve one specific task. This architecture enables the seamless extension of a system by adding new services corresponding to predefined interfaces. For example, if a new mining company enters the market or connects its databases to the global system, no changes to the system are required, as the new company is added to the existing list of service providers.

The extension of the presented ontology-based architecture by semantic web services basically enables three features: Automatic web service discovery, automatic web service execution and automatic web service composition and interaction (McIlraith et al., 2005). Thus, new or existing web services can be searched and discovered based on their well-defined semantics using automated reasoning. Their execution is automated through semantic definitions of the expected input and output values and their composition and interoperation is enabled through exact annotations covering the interfaces between services. To implement these concepts, there is a number of standards related to SOA and the semantic web. For defining web services, the XML-based Web Services Description Language (WSDL) is commonly used (www.w3.org/TR/wsdl20/). To introduce semantic concepts to the web service definition, the standard OWL-S is being developed, complementing the WSDL with semantic features (www.w3.org/Submission/OWL-S). Listing 1 shows a shortened semantic web service definition using OWL-S for the use case of identifying if a specific product uses a critical commodity:

```
<ResourceCriticalityProfile rdf:ID="Profile_Resource_Criticality">
    <profile:serviceName>ResourceCriticalityService</profile:serviceName>
    <profile:hasInput>
        <profile:Input rdf:ID=″GlobalResourceOntologyProductSelection″>
            <profile:parameterType rdf:datatype="&xsd;#anyURI">
                http://some.domain/globalReferenceOntology#Product
            </profile:ParameterType>
        </profile:Input>
    </profile:hasInput>
    <profile:hasOutput>
        <profile:Output rdf:about=″GlobalResourceOntologyCriticalityOutput″>
            <profile:parameterType rdf:datatype=″&xsd;#anyURI″>
                http://some.domain/globalReferenceOntology#ChemicalElement
            </profile:parameterType>
        </profile:Output>
    </profile:hasOutput>
</ResourceCriticalityProfile>
```

Listing 1: A semantic service definition using OWL-S

This web service receives some "Product" from the prior defined global reference ontology as input and returns a "ChemicalElement" from the same ontology, which might be used by a company checking if one element used in a new product is actually critical. A service based on this semantic service definition has been implemented. Therefore, a subclass "CriticalElement" has been defined using the definition "`ChemicalElement and hasDeposit max 1 Reserve`", while "Reserve" is defined as "`(hasExhaustionCostsPerTon some integer[>0]) and (hasExhaustionCostsPerTon some integer[<4])`". Based on these definitions, the following SPARQL (http://www.w3.org/TR/rdf-sparql-query/) query (see Listing 2) implements the above semantic service definition by returning all products that use critical elements:

```
SELECT ?Product ?ChemicalElement
WHERE {
?Product rdf:type rmo:Product .
?Product rmo:uses ?ChemicalElement .
?ChemicalElement  rdf:type rmo:CriticalElement
}
```

Listing 2: The SPARQL query implementing the above semantic web service definition

This query on the ontology is executed by a java application using the pellet reasoner and the Jena semantic web framework (jena.sourceforge.net) and for this prototypical case returns the product „CellPhone" and the chemical element „Neodymium", that has currently only one „Reserve" in China.

As the semantic web service exactly specifies the input and output of this service, it enables automated discovery and execution and thus combines the advantages of SOA and ontologies. Thus, the combination of ontologies and SOA enables automated information exchange from distributed and heterogeneous sources and, in addition, significantly supports companies by automated decision-support.

5. CONCEPTUAL EXAMINATION

In this section, the main architectural approaches shall be validated on a conceptual level by checking if the core requirements from section 2 can be met. Table 2 shows these requirements and the related architectural approaches as their implementations. Basically, ontologies are capable of combining heterogeneously structured information and of providing means for formalized processing using reasoning, as it is pointed out in (Roser and Bauer, 2005; Guarino et al., 2009; McIlraith et al., 2005). The examples in section 4 show how this is possible in the present field of application, thus serving as a proof-of-concept. Alongside, ontologies are generally based on open standards and have from the beginning been designed for interoperability (Gruber, 1993; Guarino et al. 2009).

On the other hand, the architectural pattern of SOA can also fulfill a large number of requirements: They enable a decentralized architecture integrating distributed information sources (Erl, 2005). By standardized interfaces and service registries, they provide a modular composition of services offering dynamic integration of constantly changing information (Erl, 2005; McIlraith et al., 2005). SOA standards like WSDL and OWL-S are published by the World Wide Web Consortium (W3C) as open standards and are designed for interoperability, too (Erl, 2005; McIlraith et al., 2005). The exemplary listing in section 4 illustrates how these capabilities can be applied in the presented architecture.

Requirement	***architectural approach for implementation***
Ability to cope with heterogeneous information	Ontologies
Ability to integrate distributed information sources	SOA
Decentralized architecture	SOA
Modular composition	SOA
Dynamic integration of constantly changing information	SOA
Formalized information structures enabling automated processing	Ontologies
Open standards	Ontologies, SOA
Interoperability	Ontologies, SOA

Table 2: Requirements from section two and their implementing architectural approach

Nevertheless, this examination only takes the conceptual level into account. While a complete empiric evaluation would have to be realized with the help of the a number of companies using an information system based on the presented architecture, this is generally hard to achieve, as the proposed system will only be implemented by companies, if its adequacy is validated before. Yet, there is a middle ground enabling a more detailed evaluation without having to implement the whole system.

6. EVALUATION USING THE ARCHITECTURE TRADEOFF ANALYSIS METHOD (ATAM)

In this section, the architecture presented in section 4 will be evaluated using the ATAM (Kazman, Klein and Clements, 2000). ATAM is one of the most common architecture evaluation methods and is currently used by many software developing companies (Salger, Bennicke, Engels, and Lewerentz 2008). ATAM assesses the consequences of architectural decisions in the light of quality attributes. In addition, while ATAM is a very extensive method usually spanning over at least three days, it also allows for a lightweight application (Salger et al., 2008), that is presented here in a slightly adapted version.

ATAM consists of nine steps that are basically in a linear order. First, the method is presented to the stakeholders, as is done in these paragraphs. Second, the business drivers for the system to be designed are presented. This was done in this paper in sections 1 and 2. The third step of ATAM is to present the planned architecture, which was done in section 4. Thus, steps one to three have already been basically covered in this paper. The following six steps are to be outlined below.

In the fourth step architectural approaches have to be identified. In this paper the main approaches are ontologies and SOA. In the very central fifth step, a quality attribute utility tree is created. This tree takes the most important quality attribute goals (like "performance") of the system and refines them hierarchically to the point of specific assertions like "response time is less than five seconds". These assertions are prioritized with respect to commercial importance and architectural risks using a low-medium-high range. Figure 6 shows the quality attribute utility tree created for the architecture presented in this paper. As there is a large number of possible quality attributes (as e.g. defined in ISO 9126), only some most relevant attributes are presented here, building upon an extension of the common ATAM quality attributes. For example, the assertion "Different terminologies are integrated" has a high commercial importance and poses a medium risk within the current architecture. To allow for a broad evaluation, not only the requirements from section 2 are used as quality attributes, but also common quality attributes like performance, availability and security. Nevertheless, the covered requirements from section 2 turn out to be essential scenarios based on the prioritization.

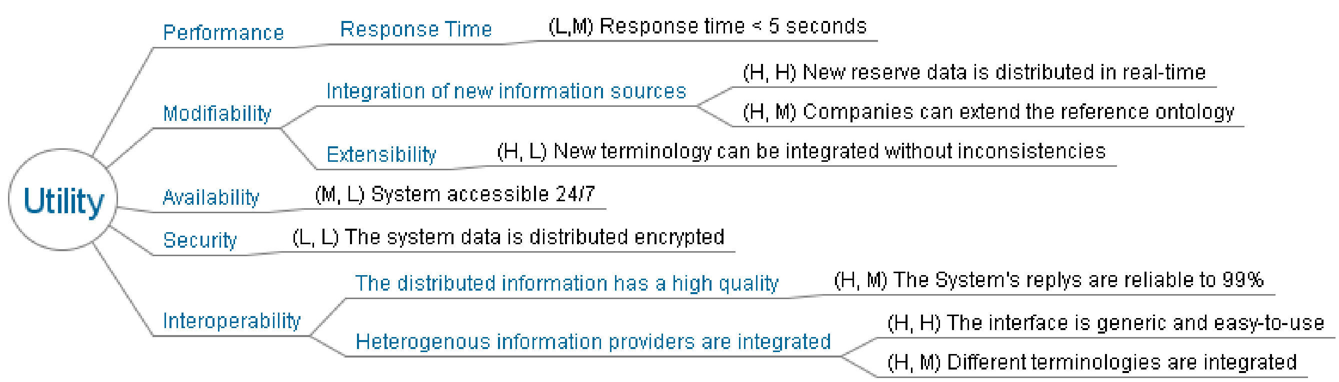

Figure 6: The quality utility tree for an information system architecture enabling sustainable management of non-renewable resources

In step six, the major identified architectural approaches are analyzed. In particular, sensitivity points, tradeoff points and risks are identified. Table 3 shows the analysis of two architectural approaches, based on use cases corresponding to utility tree scenarios.

Scenario 1: A mining company changes the reserves of a specific mine

Attribute: service-oriented architecture

Response: The data on reserves is updated autonomously

Architectural decisions:
Decentralized information storage
Risk: wrong data – **Tradeoff**: availability – **Sensitivity**: compatibility to central specification of reserves

Reasoning:
Decentralized information storage enables autonomous editing of information on its source and thus makes the system highly distributable, but reduces availability and depends on the compatibility of the new information to the specification.

Scenario 2: A producing company requests criticality information on a specific raw material

Attribute: ontologies

Response: The system acquires all relevant information, integrates and processes it and returns the overall criticality rating

Architectural decisions:
Ontology-based combination of multiple information sources
Risk: inconsistent information – **Tradeoff**: performance – **Sensitivity**: complexity of relevant ontologies

Reasoning:
An ontology-based combination of multiple information sources provides a broad basis of information at the cost of performance depending on the complexity of the used ontologies, that show the risk of being inconsistent.

Table 3: An analysis of two ATAM scenarios treating the proposed ontology-based service-oriented architecture

After these key architectural approaches have been analyzed, step seven comprises of an additional scenario brainstorming and prioritization, resulting in a list of new scenarios that can be compared with the scenarios from the utility tree. This step serves as additional checkup for the results of step five. Step eight has the same goal just as well: There the analysis of the architectural approaches is reiterated using the result of the scenario analysis, producing no new results if the prioritized scenarios have already been subject to architectural analysis, which is assumed to be the case here. Finally, in step nine, the results of the ATAM are presented.

While a more detailed application of ATAM would surely be worthwhile, this shortened application of ATAM to the presented architecture shows that the main approaches are basically sound with respect to the most important quality criteria. The quality utility tree shows that the addressed approaches are in fact critical to the success of the systems, while the scenarios combined with the prototypical proof-of-concept implementation in section 4 show that they can fulfill their requirements. Thus, ontology-based information system architectures using SOA can effectively contribute to an improved management of non-renewable resources.

7. CONCLUSION AND FUTURE WORK

The previous sections have analyzed if an ontology-based service-oriented information system architecture can improve the sustainable management of non-renewable resources and have presented an architecture and a prototypical evaluation for this purpose. After a motivation in section 1, section 2 has listed core requirements for such a system. In section 3 fundamentals of the proposed architectural approaches have been outlined. The architectural design, its core architectural approaches and a prototypical implementation are described in section 4, followed by a conceptual evaluation in section 5 and an evaluation using ATAM in section 6. This section serves as a conclusion and an outlook.

Basically, ontologies and SOA provide many of the required capabilities. In fact, the combination of ontologies and semantic web-services potentially enables the automated exchange of distributed and heterogeneous information sources and gives reason for very optimistic expectations regarding future possibilities of semantic and service-oriented information networks. Nevertheless, ontologies and semantic web services still pose many challenges to the developer, partially due to their complex logical structure and also partially due to the early stage of development of many tools and libraries. Though, deducing from the present results the technical feasibility generally seems to be given.

As a next step, the industrial evaluation in cooperation with business partners is one central objective. In doing so, the presented architecture can be practically evaluated and optimized. Nevertheless, prior to a broad range implementation of ontology-based web services, a process of standardization has to be initiated, for what this paper offers some early contribution. In this context, it is also planned to provide public access to the developed ontologies to enable cooperation with other research groups and companies, thus moving towards a multifaceted semantic network to improve the information on and thereby the management of non-renewable resources.

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