

AN ONTOLOGY-AIDED OPTIMIZATION APPROACH TO ECO-EFFICIENT BUILDING DESIGN

Ferial Shayeganfar¹, Amin Anjomshoaa², Johannes Heurix², Christian Sustr¹, Neda Ghiassi¹, Ulrich Pont¹, Stefan Fenz², Thomas Neubauer², A Min Tjoa², Ardeshir Mahdavi¹

¹Department of Building Physics and building Ecology,
Vienna University of Technology, Vienna, Austria
²Institute of Software Technology and Interactive Systems,
Vienna University of Technology, Vienna, Austria

ABSTRACT

Despite the advances in development of building performance simulation tools, their potential for performance-guided design has not been sufficiently exploited within the design community. This is in part due to the complexity of data accumulation for simulation purposes and the elaborate data entry modalities of available tools. The web undoubtedly contains extensive supplies of potentially useful information. However, the extraction and application of this data is hampered by lack of sufficient structure in the encapsulation and presentation of the information. The present paper reports on the progress of the SEMERGY project in exploring this web-based potential using semantic web technology to extract and restructure building product information into an ontology integrated within a performance based design optimization environment.

INTRODUCTION

Over the past few decades, many efforts have been made to tune the building design process for production of energy efficient buildings. Development of various building performance assessment tools ranging from simple normative calculation engines to highly complex performance simulation software is a major outcome of these efforts. However, the uptake of such tools in the building design process remains very limited. Traditionally, rules of thumb and simplified calculations have been used to guide thermal performance considerations during the early design stages of buildings. It is only after the design has been finalized that external energy analysts have been involved to analyze the final design solution (Hensen et al. 2004), whereas the simulation tools can be used more efficiently to support the generation of design alternatives, or to make informed choices between different design options, or to optimize building and/or systems (De Wilde 2004).

Contrarily to this general tendency, studies show that decisions taken during conceptual design have a disproportionate impact on the final building performance, relative to time and effort consumed (Domeschek et al. 1994). Moreover, the cost of implementing changes during the early stages is

substantially lower than in later phases of the design process (McGraw-Hill 2007). Building performance simulation is rarely used at all for supporting early design phase tasks such as feasibility studies and conceptual design evaluations (De Wilde 2004).

The insufficient adoption of Building Performance Simulation tools may be attributed in part to the complexity of data accumulation for simulation purposes, the elaborate data entry modalities and usability issues of available tools.

The web undoubtedly contains extensive supplies of potentially useful information which can facilitate the data accumulation and entry. However, the extraction and application of this data is hampered by lack of sufficient structure in the encapsulation and presentation of the information (Mahdavi et al. 2012a).

The SEMERGY project (Mahdavi et al. 2012a, Mahdavi et al. 2012b) intends to bridge this gap by providing semantic links between real world products and building model's abstract concepts and elements.

The gap between required and available Architecture, Engineering, and Construction (AEC) data sets is hypothesized to be bridgeable based on two main pillars: First, a set of compact and versatile ontologies should be created that serve as a shared standard vocabulary of AEC concepts. The real world products can be then described via these vocabularies in a uniform machine-processable format. Secondly, the building performance assessment and optimization environments should be linked to these product descriptions for exploration of design alternatives and evaluation of energy efficiency.

The key contribution of the research is the exploration and demonstration of the Semantic Web technologies (Berners-Lee et al. 2001, Berners-Lee et al. 2006) toward populating the input data for building performance simulation models via the navigation of the extensive but currently ill-structured web-based information space pertaining to building materials, elements, components, and systems, as well as resources and documents concerning procedural, climatic, and financial (e.g., public funding) information that could be of value to designers and decision makers.

In order to clarify this process we will first explore the major use-case of SEMERGY project. As mentioned before this project concentrates on design optimization in view of multiple criteria of investment and operation costs, energy performance and environmental impact. For this purpose, the initial design is conveyed by the user via a web-based user interface in the form of a building data model containing information such as geometry, building components and their properties, along with additional background information concerning available budget and/or desirable or intended performance objectives.

In a second step, SEMERGY considers a number of semantic (non-geometric) permutations of this initial information to create valid construction alternatives for different building components. The underlying reasoning interface responsible for the identification of these alternatives holds a set of rules derived from an analysis of common building constructions based on different product properties. Product libraries play an important role for providing appropriate products that match the user/design requirements. For this purpose, SEMERGY system employs semantic web-technologies in order to capture and formulate the required information in a dynamic and machine-processable format.

Finally, a comprehensive evaluation process will be executed. Thereby, both simplified calculation routines (e.g., those necessary to generate energy certificates for building projects or perform life-cycle analyses) and numeric simulation applications (e.g., thermal performance simulation tools) could be deployed (Mahdavi et al. 2012a).

BACKGROUND

Nowadays, the Building Information Modeling (BIM) methods are being used intensively in different processes of building design, construction, operation, and maintenance. In this context, BIM uses a schema to define the main concepts and a number of local names and descriptions. In order to achieve the interoperability at global level, the schema concepts should be separated from local names and descriptions. This separation could be realized via dedicated dictionaries of construction terminologies that cross the regional and language borders and uniformly define the meaning of terms such as product names, properties, etc. The International Framework for Dictionaries (IFD) is aiming to establish such a standard library, where concepts and terms are semantically described and given a unique identification number (Bell et al. 2006). More explicitly the IFD is an ISO standard (ISO 12006-3) that is described using an EXPRESS model with a short explanation of its purpose and use. IFD libraries are more than a simple mapping of words among various languages and provide an abstraction layer that contains the conceptualization of entities. This abstraction layer will then facilitate

connecting the entities via shared library concepts. For instance the word “Tür” in German is mapped to the same library concept as the English word “door”. So manufacturers may introduce their products in the international market without being hampered due to language issues. The IFD library will handle the representation of products in other languages by aligning the product specifications to the IFC reference model. Moreover an entity might be interpreted differently in different countries and again an IFD can address this issue by providing an abstract reference library. An important role of IFD library is the separation of a concept from its local names and descriptions that define that concept. In IFD this is achieved by separating the concepts from the names and descriptions that are used to name and describe it. As a matter of fact, the IFD library let the concept be both described by multiple name and descriptions and also its relation to other concepts.

Several countries have started building dictionaries based of IFD. The most important libraries for building smart are BARBi (Bell et al. 2004) and LexiCon (Woestenenk 2002), which are defined for a better communication between construction partners and for better information handling by computers. Some research works have tried to harmonize IFC with IFD structure (Jansen et al. 2003). By using globally Unique ID (GUID), all the information in the IFC format can be tagged and the concepts may be defined in any language and can be processed by computers. It means that these GUID are used by machines to process the data and textual descriptions by humans.

In 2009, the IFD library group has become a part of buildingSMART International (bSI) and since then, the integration of IFD Library into bSI has progressed with plans underway to transfer the IFD Library Intellectual Property to bSI. Later on in September 2010, the IFD Library was renamed to buildingSMART Data Dictionary to fit in with the renaming of the IFC standard to buildingSMART Data Model, and the IDM standard to buildingSMART Processes (NBIMS 2012).

Several other research projects have been done over the years on IFC model in order to develop modeling and implementation of AEC objects and to provide more integrated, interoperable and intelligent AEC objects (Halfawy et al. 2002). Some of them have tried to provide online product libraries for AEC industries based on IFC and present the architecture for implementation with aim to support industry practices in the production and consumption of product information (Owolabi et al. 2003).

Another trend in product libraries follows the Semantic Web and ontology principles to define the required concepts and their properties. Having a semantically enriched, searchable library of building products can support designers to efficiently select those products that best match design constraints and

criteria pertaining to specific projects (Shayeganfar et al. 2008, Beetz et al. 2009, Issa 2012).

The SkyDreamer project (Shayeganfar 2009) provided a prototypical combination of BIM and semantic technologies for the selection of energy-efficient products (skylight components). This research provided a proof of concept in view of the potential of elaborate semantic technologies toward bridging the knowledge gap between manufacturers' data, building information models, and simulation web services.

The Building Component Library (BCL) (Fleming et al. 2012) is another online repository of components and measures that is aiming to address the specific requirements of Building Energy Modeling (BEM) which are not covered by BIM. The BCL repository currently contains around 30,000 components and measures and provides uniquely identified components that can be cited, validated, and reused by BEM community. Unlike BCL components which are stored and retrieved in XML format, the SEMERGY project is benefiting from Semantic Web technologies which provide better possibilities for data integration, data sharing, and interoperability on the web.

ONTOLOGY ENGINEERING

In this section, the core process of establishing SEMERGY ontology and the design considerations will be discussed in detail. This includes the process of semantifying Baubook product database which is a well known product repository for building products in Austria.

Product Hierarchy

For realizing the project goals and as proof of concept, we have decided to use Baubook web platform (Baubook 2013) as one of the main resources for building product and components. The Baubook web platform is a database of building products with their ecological and physical properties. Building product manufacturers can define their products, which will be evaluated and classified according to their physical attributes (e.g., such as conductivity, specific heat, density, etc.) and ecological attributes (e.g., global warming potential, acidification potential, etc.). Furthermore, the cross references between building products, the building code provided by local authorities, and governmental funding resources such as grants, tax-credits, loans extend the visibility and navigability of building elements in the building industry.

In order to semantify the data, we have first adopted the Baubook categories and formatted them as the main hierarchy of SEMERGY ontology. This task is done by a customized RDFizer component that reads the original Baubook categories and converts them to hierarchy of RDF (Klyne 2004) classes in SEMERGY ontology. Figure 1, depicts part of the converted class hierarchy.

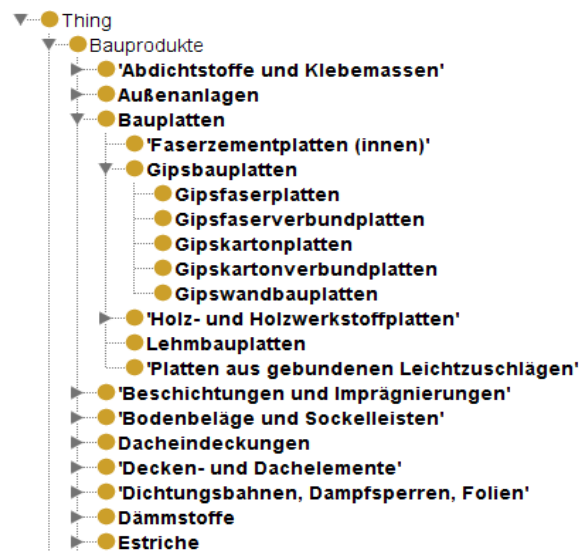


Figure 1 SEMERGY's product hierarchy

After having the class hierarchy in place, the Baubook products are also extracted and converted to RDF format via a dedicated page parser. During this process aside from the existing Baubook product properties, some additional properties are calculated and attached to imported products. An example of such derived property is the thermal resistance (R-value) which can be calculated and asserted based on the thickness and thermal conductivity values. These internal calculations help reduce the calculation load in the assessment procedure.

In order to keep the relationship between the imported product and its corresponding web resource, the *owl:sameAs* axiom is used which connects the URI of web resource to the product description. Figure 2, depicts a typical Baubook product with the extra property for defining the corresponding web resource.

Resource Form	
Name:	semergy:baubook_2142707193
Annotations	
rdfs:comment	Nichtbrennbare Akustikplatte aus Blähglasgranulat für abgehängte Decken- und Wandkonstruktionen; Eigenschaften: fugenlos bis 200 m ² verlegbar, geringes Gewicht und hohe Steifigkeit, geringe Feuchte- und Wärmeausdehnung; Hinweis: Montageanleitung beachten, nichtbrennbar (@de)
rdfs:label	StoSilent A-Tec Panel Alu
owl:sameAs	http://www.baubook.at/m/PHP/Info.php?SI=2142707193
Other Properties	
semergy:acidificationPotential	0.00896
semergy:bulkDensity	325
semergy:globalWarmingPotential	2.433
semergy:notRenewablePEI	40.99
semergy:r-value	0.61
semergy:specificHeatCapacity	900
rdf:type	owl:NamedIndividual semergy:Platten_aus_gebundenen_Leichtzuschlägen

Figure 2 Semantic Product Description

Ancillary Product Properties

In addition to the existing product properties in Baubook, for the rule based reasoning interface to function, further details regarding the form and functions of products are needed. This information which is not included in Baubook, is of great importance for assigning alternative materials to different building elements. For instance, a gypsum board, which is moisture-sensitive, is not appropriate for exterior usage and therefore it should not be suggested as an alternative material for external wall finishes.

These properties establish a class hierarchy in the SEMERGY ontology and are categorized for layers as follows:

- **Functions:** this group of properties is dedicated to functional aspects of building products that may serve as a layer in different component configurations such as wall, ceiling, or roof components. Examples of functional categories under this group include insulation, load bearing elements, and protective foils.
- **Position in Assembly:** this group also deals with layer properties of products and includes model-specific aspects of building in view of appropriateness for deployment in different parts of the building construction such as roof, ceiling, window (e.g. roof-suitable, wall-suitable, ceiling-suitable, etc.)
- **Format:** this group includes categories to describe physical properties and shape of the products. Block, plate, and foam are examples of subcategories under this class.
- **Material:** this group identifies the constitutive material of a product (e.g., wood, concrete, glass, metal).

Figure 3, depicts the class hierarchy for layer categories and also the details of format sub-category.

semantic reasoner, the instances of Baubook categories (products), are also classified under SEMERGY properties.

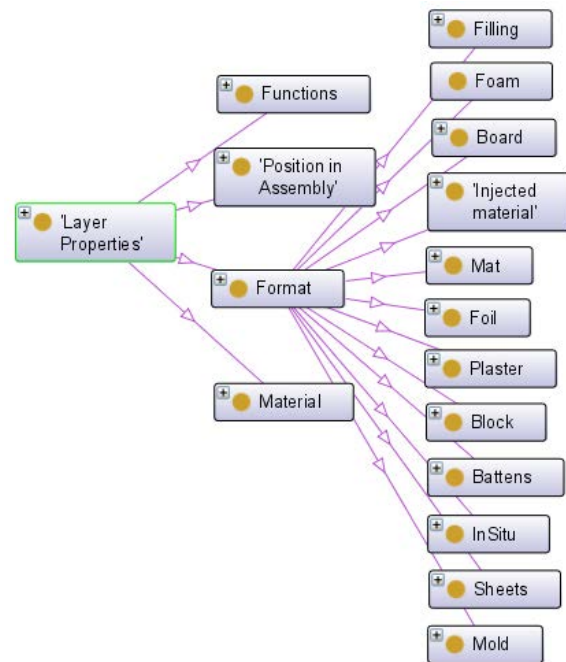


Figure 3 SEMERGY's Ancillary Properties for Format category

It is important to note that a single product is usually connected with a number of SEMERGY's property classes. In semantic terms, the categories of a product class are documented as super-classes of that product class. As a result, all products (i.e., instances) of that class are also inferred to be instances of relevant super-classes. For example, consider the wall element depicted in figure 4. Since this wall element is a subclass of some SEMERGY properties such as Load Bearing, Heavy, and Solid, the corresponding products of this wall type can be also queried under these super classes. Consequently, we can create efficient queries that meet specific requirements of SEMERGY use-cases.

Enriching Baubook Hierarchy

In the previous two sections, we have described the Baubook product hierarchy and also the property hierarchy of SEMERGY project. Since the Baubook only incorporates certain industry relevant product properties, it cannot provide all required information for the imbedded reasoning procedure. As a result, the Baubook hierarchy should be enriched to include the extended set of product properties.

Fortunately, the semantic data model, is very flexible in terms of expressing the interrelations among domain classes.

In case of SEMERGY ontology, we have established the connection between Baubook classes and extended properties via adding subclass axioms between these two class hierarchies. In other words, after creating subclass relationships and running the



Figure 4 SEMERGY-Baubook mapping

The other improvement that has been done regarding Baubook hierarchy is to set a default product for each category. These default products, which are selected based on their commonness of use, are used to enrich the initial design model for calculation and simulation purposes. To do this, we would need to connect some specific products (represented as instances in SEMERGY ontology) to Baubook classes. These special instance-to-class relationships are described via dedicated annotation properties that are added to target classes.

According to SEMERGY use-cases, each product category needs two default products for novice and expert users. The reason for this decision is that on the one hand some real world product names include technical terms that are not easy to understand for the non-experts. On the other hand, expert users need fine-grained information to improve their design decisions. Accordingly, two annotation properties, namely *(hasNoviceDefaultProduct)* and *(hasExpertDefaultProduct)* are defined to satisfy the requirements of each user group. Figure 4 depicts the default products for novice and expert users that are assigned to a specific wall product category.

SEMANTIC QUERIES

After establishing the Ontology, the product alternatives for different building components should be extracted and sent to the evaluation and optimization procedure in order to rank and benchmark the alternative solutions based on environmental, economical and energy performance metrics. For this purpose, a semantic data interface has been implemented that functions as mediator between SEMERGY's software components and the semantic repository. On the one hand, it translates the design constraints and requirements as semantic queries in SPARQL (SPARQL 2013) format. On the other hand, it is responsible for mapping the extracted RDF data and query results to required objects in SEMERGY Building Model (SBM). In general, this Semantic data interface includes a set of SPARQL query components instead of static pre-defined queries, which allows the interface to dynamically compose the desired queries at execution time. For example, the interface allows to query by type, class, property (or its value), as well as apply filters on SEMERGY-specific expressions. This allows for maximum adaptability should the need for new query types or semantic changes in the Ontology arise. Using the SPARQL interface of product repository, a wide range of constraints and user requirements can be addressed. In SEMERGY use-cases, the constraints are usually divided into two main categories:

- Product type constraints where the SPARQL query includes Baubook's product class and/or SEMERGY's extended classes as explained in previous section.

- Product property constraints that consider range limitations for property values of target product such as thermal conductivity, price, or thickness.

The SPARQL queries in SEMERGY system typically include a combination of the above mentioned constraints. As an example, consider the case of searching for a Wood-Concrete wall element with a thickness under 30 cm and a thermal conductivity under $0.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. In this case, the data interface uses the query components involving the product type, thickness, and conductivity to create a suitable query. Listing 1 demonstrates the resulting SPARQL query that addresses these.

```
SELECT ?name ?conductivity ?thickness
WHERE {
  ?product a semergy:WoodConcreteWallElement.
  ?product rdfs:label ?name .

  ?product semergy:thickness ?thickness .
  FILTER (?thickness < 30) .

  ?product semergy:thermalConductivity ?conductivity .
  FILTER (?conductivity < 0.5)
}
```

Listing 1 Sample Product Query

Figure 5 depicts the results of this query and possible product alternatives.

[name]	conductivity	thickness
Thermo-Span IW 25/19 Schallschutzsteine	0.463	25.0
Thermo-span IW 15/9 Innenwandsteine	0.300	15.0
Thermo-span IW 18/12 Innenwandsteine	0.344	18.0
Thermo-span IW 20/13 Innenwandsteine	0.333	20.0
Thermo-span IW 22/15 Innenwandsteine	0.353	22.0
Thermo-span IW 25/16 Innenwandsteine	0.321	25.0
Thermo-span Thermo-S 25/6 WDV	0.132	25.0
isospan Dünwandstein I25	0.384	25.0
isospan Innenwandstein N18	0.348	18.0
isospan Innenwandstein N20	0.334	20.0
isospan Innenwandstein N22	0.355	22.0
isospan Normalwandstein N25	0.323	25.0
isospan Super 2000 S25/6	0.140	25.0

Figure 5 SPARQL Query Results

The aforementioned approach can be also generalized to compound building components such as walls, which may have multiple layers and a number of property requirements for each single layer. Suppose, for example, that a specific building design requires an insulated single-leaf brickwork wall with naturally-ventilated facade element (Cheret 2010). Typically, the construction details of such compound products are defined in building construction code and standards in a product-neutral form. For instance, the layers of this specific wall can be defined as shown in Table 1.

LAYER NAME	PROPERTIES/RESTRICTIONS
1. Interior finish	Format: Plaster Material: Gypsum, Lime, ... Misc.: Wall-suitable
2. Brickwork	Format: Block, ... Material : Brick, Stone, ... Misc.: Non-deformable, ...
3. Insulation	Format: Plate, Mat, Foam Material: Cork, Sheep wool, ... Misc.: Wall-suitable
4. Rear-ventilation	Format: Material : Air Misc.:
5. Facade	Format: Plate, ... Material: Wood, Glass, Metal, ... Misc.: Moisture-resistance, ...

Table 1 Definition of a layered wall

As shown in Table 1, the layers can be described via the SEMERGY property classes that were discussed in previous sections. Since these property classes are also interconnected with Baubook products, the appropriate query on these properties would fetch the suitable real-world products from Baubook repository. Thus, for the above mentioned use-case, the property classes in the second column will be used to prepare the SPARQL query for each layer. For instance the query for the facade layer may look as shown in Listing 2.

```

SELECT ?product ?name
WHERE {
  ?product a semergy:Plate.
  ?product a semergy:Wood.
  ?product a semergy:Glass.
  ?product a semergy:Metal.
  ?product a semergy:Moisture_resistance.
  ?product rdfs:label ?name .
} LIMIT 20
    
```

Listing 2 Sample Product Query

After selecting the appropriate products for each layer, the wall construction alternatives can be built based on the Cartesian product of resulting products for each layer. As this approach usually produces a large number of alternative solutions, they need to be further filtered according to other constraints such as maximum costs, thus reducing the number of valid solutions to a manually manageable size.

CONCLUSION

The research presented in this paper shows how elaborate semantic technologies can be used to bridge the information gap among manufacturers' data, building information models, and performance assessment web services. In future the proposed approach will be applied to other online product libraries (e.g., MASEA 2013) in order to demonstrate the capacity of a semantically enriched process and

how it helps the designer to find the desired product through automated access to the building product libraries. The key contribution of the research is the exploration and demonstration of the semantic web technologies toward populating the input data for calculations and simulations via the navigation of the extensive but currently ill-structured web-based information space pertaining to building materials, elements, components, and systems, as well as resources and documents concerning procedural (e.g., legal), climatic, and financial (e.g., public funding) information that could be of value to designers and decision makers. The current work is expected to support the development of a data representation format for product manufacturers which is compliant with informational requirements of energy performance assessment applications, yet includes other aspects of building products such as ecological indicators and price information.

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