Shape-Function-Relationship (SFR) framework for semantic interoperability of product model

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Abstract: The problem of semantic interoperability arises while integrating applications in different task domains across the product life cycle. A new Shape-Function-Relationship (SFR) framework is proposed as a taxonomy based on which an ontology is developed. Ontology based on the SFR framework, that captures explicit definition of terminology and knowledge relationships in terms of shape, function and relationship descriptors, offers an attractive approach for solving semantic interoperability issue. Since all instances of terms are based on single taxonomy with a formal classification, mapping of terms requires a simple check on the attributes used in the classification. As a preliminary study, the framework is used to develop ontology of terms used in the aero-engine domain and the ontology is used to resolve the semantic interoperability problem in the integration of design and maintenance. Since the framework allows a single term to have multiple classifications, handling context dependent usage of terms becomes possible. Automating the classification of terms and establishing the completeness of the classification scheme are being addressed presently.

Keyword: Aero engines, SFR framework, Product Ontology, Product Data Exchange, Semantic Interoperability

1 Introduction

To achieve competitive advantage nowadays, most of the companies have to manage the product (such as aircrafts, automobiles, boats and bicycles etc…) information throughout its entire lifecycle ranging from design, manufacturing, assembly, inspection, maintenance, operation, reuse and retirement. The product information includes not only the geometric and shape but also the higher level of product information where designers/ engineers can attach information required to support decisions (related to designing, manufacturing, operation, maintenance etc…) and can be used for later stages of product lifecycle such as operations, maintenance and sales. Sometimes two terms/ labels refer to a single part/ system in different applications. For example, terms Blast Chamber, Combustion Chamber, Firing Chamber, and Combustor refer to the same part as these terms have same meaning. The information may contain terms/ labels for a part/ system having different meanings in different applications. The mismatch in terms/ labels for a part/ system generates ambiguous information and multiple representations which lead to the wrong decisions or failure. Now it is required to identify and exchange information in the presence of mismatch in terms/ labels for a part/ system used in PLM system (Product

Lifecycle Management) to provide the right information at the right time for the right decision. As applications are geographically distributed, the semantic interoperability becomes more important to support today's globally distributed environment.

Semantic interoperability in the shape domain can be addressed by reasoning about geometry alone [1, 2]. However when domains such as operations and maintenance are involved shape information is insufficient to capture semantic information of different parts/ systems used. This is because labels of two parts/ products with same shape are different because they serve different functions. Authors are therefore proposing Shape-Function-Relationship (SFR) framework to capture semantic of a part/ system of an aero engine used in different stages of PLM e.g. manufacturing, operation, maintenance, sales catalogue etc... SFR structure provides unique representation of a part/ system. Ontology-driven SFR framework, based on explicit definitions of terminology and knowledge relationships in terms of shape, function and relationship descriptions, offers an attractive approach for solving semantic interoperability issue. Elements of SFR framework with ontology has been described in the following sections. The framework is presented for aero engine as to clarify elements of SFR structure with developed ontology. The reasoning module has been demonstrated with a case study for aero engine.

2 Literature review

The problem of semantic interoperability has been addressed primarily in the domain of shape modeling in the context of exchange of CAD models between different CAD systems [1-4]. A different flavour of this problem manifests while integrating applications in different task applications across the product life cycle. For instance, integrating design and maintenance applications will require handling multiple terms used for the same entity as the maintenance information is often created by different actors. Tasks such as information retrieval for design reuse also encounter the interoperability problem. There are two broad approaches in the literature to address this problem. The first uses multiple ontologies (specific to each application) and providing mapping between these multiple ontologies to match terms/ entities with same semantics [5, 6]. The mapping involves both syntax and semantics. The second approach involves the development of a single ontology by capturing, through enumeration, synonyms of entities in use [7-9].

The use of ontologies to address the information extraction problem has been addressed by several researchers. Papers [5, 6] focus on unstructured design documents and address the problem of improving information retrieval and extraction using ontology. They use a shallow NLP technique to automatically populate ontology instances according to domain ontologies. Compared to a keyword-based retrieval method, the proposed method is able to retrieve larger number of correct documents by exploiting the hierarchical organization of concepts. A total number of six domain ontologies, device, performance, function, material, manufacturing process, and environment, are used as domain ontologies. Multiple taxonomies are used to build an Engineering Ontology and the relationships are found across these taxonomies. Taxonomy is used to classify parts/ words/ phrases (called concepts) that appear in a domain. Each word/ phrases may appear many times in different taxonomies and resolving the ambiguity is computationally very expensive as described in papers. Ambiguities are resolved by referring to the content of the words/ phrases that match with multiple concepts. The domain/ taxonomy name has to be in query to find a particular concept.

The paper [9] reviews recent works on ontologies in engineering domain and compared them using pre-defined comparison criteria. These ontologies are mainly used to address the interoperability problem due to heterogeneity in data models. The paper [8] describes a six stage methodology for building an ontology for engineering design that composed of four root concepts, i.e. Issue, Product, Function and Design Process. The application is to improve indexing and retrieving information from unstructured documents. Each term in the ontology has a label name (visible to users) and its synonyms.

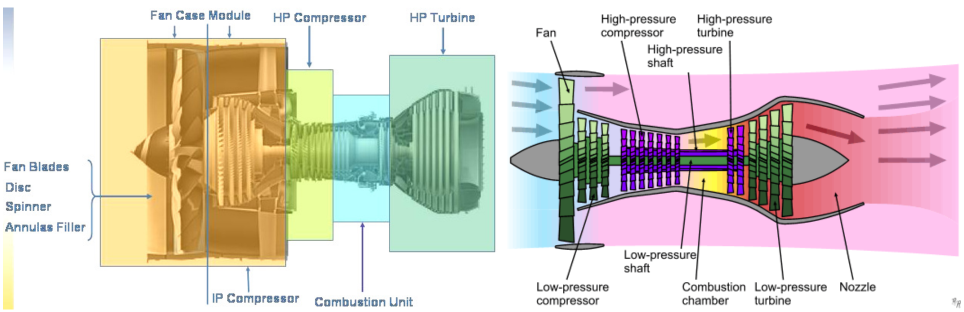
The paper [7] presents an ontology-based document management approach focusing on information extraction and users' comments. The proposed solution uses an automatic identification of named entities (NE) through information extraction (IE) technique and document searches based on NE. Sample texts (137 documents) have been analysed in order to identify how 'Product' names were referred to in texts.

The work published in papers [1-4] is focused only on exchanging shape information, where shape information is used to describe features in a product model. The paper [2] has used DIFF model [10, 11] to describe shape information of a product model and DIFF ontology is developed to resolve semantic interoperability. DIFF structure provides a unique representation of features in a product model. The reasoning module with examples is described in the papers.

3 Aero – engine

The most common type of aero engine is the turbojet engine. Air from the atmosphere enters into the fan section at the front of the engine where it is compressed in the compressor section. Then it is forced into combustion chambers where fuel is sprayed into it and ignited. Gases that form expand rapidly and are exhausted out the rear of the combustion chamber. The energy from these gases spins the fan-like set of blades called a turbine, which rotates the turbine shaft. This shaft, in turn, rotates the compressor, thereby bringing in a fresh supply of air through the intake at the front of the engine. The rest of the energy is expelled out through the tail pipe or propelling nozzle, providing forward thrust. Adding an afterburner section, where extra fuel is sprayed into the gases as they are exhausted and the fuel burns, adds thrust. Some parts of an aero-engine are shown in figure 1.

Figure 1 Parts of an aero-engine [12, 13]



4 Semantic information exchange

When integrating applications, substantial difficulties can arise in translating information from one application to the other. Applications may use different terminologies to describe the same shape. Even when applications use the same terminology, they often associate different semantics with the terms or represent different parts/ systems. This obstructs information exchange among applications. The authors are focusing on identifying and capturing the terms/ labels of parts/ systems and enabling semantic integration of disparate information throughout the Product Lifecycle. Our work proposes an ontology based approach to enable such semantic interoperability.

4.1 Types of semantic interoperability

There are two types of semantic interoperability issues to be handled as required while exchanging information among applications. Work is specific to the use of aerospace terms.

i. One part/ system (entity) has two or more names
ii. Two or more parts/ systems (entities) have same term/ name

These types of semantic interoperability issues have been described with examples in the following subsections.

4.1.1 One part/ system (entity) has two or more names

This case refers to one part having multiple labels. Terms used may refer to a part / object with in an application as shown in table 1. For example the part "Combustion Chamber" may appear in documents as Blast chamber, Combustion chamber, Burner, Chamber, Firing chamber or Combustor. Similarly, Afterburner is also referred to as "Reheater" in some geography. A list of linguistic features (Singular/ plural, Acronym, Syntactic variation, Lexical variation, Compounds words pattern, Separate reusable suffix, Separate reusable modifier, Context) with their examples are described in paper [7]. These variations are come under this type of semantic interoperability issue. The papers [7-8] have solved this type of semantic interoperability issue by grouping and enumerating terms under synonyms of one term.

Table 1 One part/ system (entity) has two or more names

Part	Part names/ terms
Combustion chamber	Blast chamber, Combustion chamber, Firing chamber, Combustor
Rotor blade	Rotor blade, Impeller blade, bucket, Rotating blade
Turbine wheel	Disc, Drum, Turbine wheel
Blade	Vane, Blade , Bucket

4.1.2 Two or more parts/ systems (entities) have one name

One name/ label may refer to two or more parts. Example of this type of issue is the label blade that could be referring to a compressor blade, turbine blade, stator blade or rotor blade (table 2). A part name/term has multiple representations referring to multiple parts. Though the parts have commonalities at higher levels of abstraction, the distinctions appear at a more detailed level. For example Compressor Stator Blade and Turbine Stator

Blade have some common features but represent different parts. It is context dependent but the context may not be explicitly defined in the text or may be defined somewhere.

Table 2 Two or more parts/ systems (entities) have one name

Part name/ term	**Part**		
	I	**II**	**III**
Blade	Vane	Bucket	
Compressor Blade	Rotor blade of Compressor	Stator blade of Compressor	
Disc	Fan Disc	Turbine wheel	Compressor Disc
Case	Fan Case	Turbine Case	Compressor Case

Authors propose to describe part/ system in terms of descriptors of shape, function and relationship. These descriptors are used to describe shape of the part/ system, function of the part/ system and relationship with other part/ system. The entries (instances) against these descriptors of SFR structure are used to describe part/ system uniquely.

4.2 Reasoning module

Product with its assemblies/ sub assemblies/ parts are first describe in terms of SFR structure and the description is used to reason and find equivalent terms used in required application. SFR ontology is used to capture and has semantic terms of SFR structure. The query feature of the ontology editor is used to find semantically equivalent terms for the term being exchanged. Applications such as information retrieval, search service manual, automatic plan generation, live updates are added advantages.

5 Shape-Function-Relationship (SFR) framework

Authors have defined attributes of the SFR structure as generalized as possible so that most of the parts/ systems of a product can be defined in SFR framework. A part/ system of a product can be defined uniquely in the SFR framework so as to achieve semantic interoperability among applications.

The SFR structure is used to visualize product in terms of shape of part/ assembly, function of part/ assembly and relationship of part/ assembly with other parts/ assemblies. Presently, different attributes of SFR structure are entered manually and some attributes of function will require knowledge about the product. Elements of SFR framework are described in the following subsections. The following subsection also describes how to capture semantic of a product in the SFR structure. Development of ontology based on the SFR framework is described in the next section.

5.1 Shape definition

The shape element of SFR framework is used to describe shape of the product in terms of parts in the product. These parts have form and material to describe the product. The product is linked to the product 3D model/ image to identify parts/ components in the product and their form and material. The identified values are the input values for the shape definition of the SFR structure and used in the reasoning. The attributes/ parameters used to describe the Shape element of the SFR structure is depicted in table 3.

Shape = F (Form, Material, Parts, Product 3D model/ image)
Form = F (Form of individual part in the product) = F (FP_1, FP_2, FP_3 … FP_n)
Material = F (Material of individual part in the product) = F (MP_1, MP_2, MP_3 … MP_n)
Parts = F (Parts/ components in the product) = F (PT_1, PT_2, PT_3 … PT_n)
Product 3D model/ image = F (Link of the 3D model/ image of the product)

Table 3 Attributes/ parameters used to describe the Shape element.

Form	Material	Parts	Product 3D model/ image
FP_1, FP_2 … FP_n	MP_1, MP_2 … MP_n	PT_1, PT_2 … PT_n	

5.2 Function definition

The function element of SFR framework is used to describe part/system in terms of working medium used and part/ system itself as follows.

Function = F (Working medium, Part/ system)
Working medium = F (Parameters to describe working medium, Medium _in_contact)
Part/system = F (Motion of part/ system)
Where: Parameters to describe working medium = Velocity, Pressure, Temperature in the case of aero-engine.

The attributes/ parameters used to describe the function element of the SFR structure is depicted in table 4.

Table 4 Attributes/ parameters used to describe the Function element.

Velocity of fluid	Pressure of fluid	Temperature of fluid	Medium_in_contact	Motion of part/system

5.3 Relationship definition

This element of SFR framework is used to describe product in terms of i. relationship with other parts/ assemblies based on spatial and functional sequence, ii. component of or super-assembly of as follows.

Relationship = F (Relationship with other parts/ assemblies, component of)
= F (Before, After, Component_of)

Table 5 shows the attributes used to define the Relationship element of SFR structure. The relationship definition of a product "Combustion Chamber" is also depicted in the table where attributes Before, After and Component_of have values as Compressor, Turbine and Aero engine respectively. The functional sequence in aero engine is Intake-Compressor-Combustion Chamber-Turbine-Nozzle-Exhaust (Figure 2).

Table 5 Attributes/ parameters used to describe the Relationship element.

Before	**After**	**Component_of**
Relationship definition for "Combustion Chamber"		
Compressor	Turbine	Aero engine

Figure 2 Spatial and functional sequence of an aero engine [14]

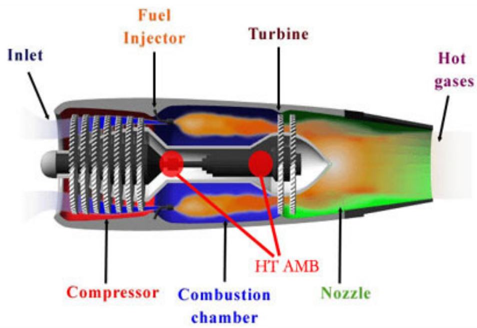
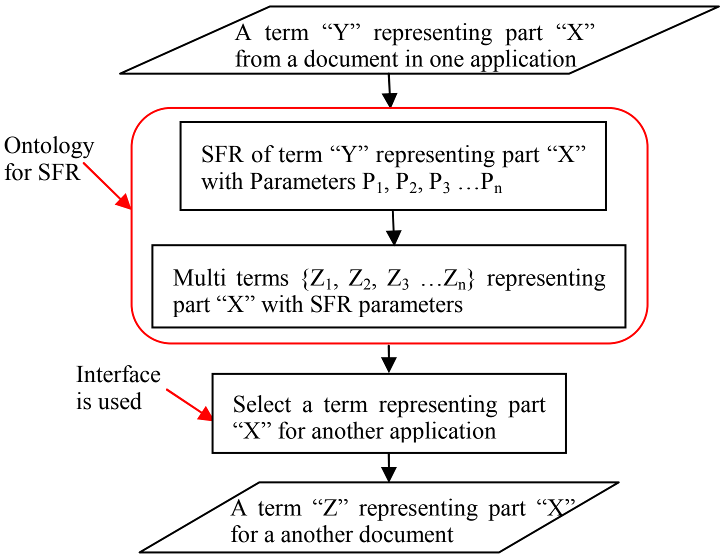


Figure 3 Schematic diagram of the process for identification of mismatch in terms/ labels for a product



5.4 Semantic definition of a product

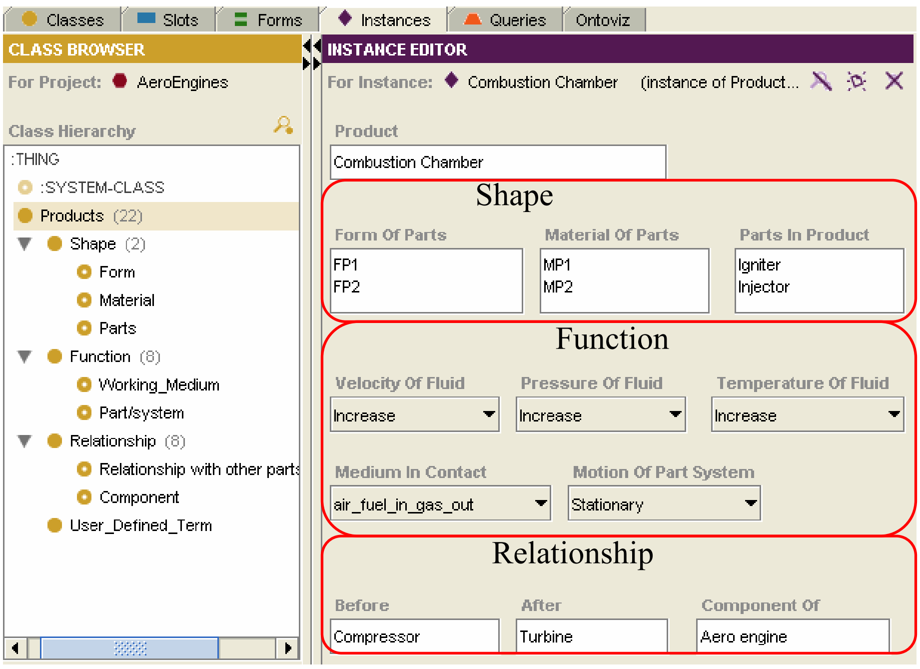
A product consists of assembly, subassemblies and parts with their relationship. Authors have analyzed and represented most commonly used terms of aero engine occurring in product, production, sales and maintenance manuals. A part can be uniquely represented by SFR structure. Sometimes the definition of one element of SFR structure is same for two products but at the same time the definition of other two elements will be different.

So a part can be uniquely represented by group of Shape, Function and Relationship elements of the SFR structure. For example, two parts (turbine rotor blade and compressor rotor blade) have the same function but difference can be captured by shape and relationship elements. If two terms have same SFR structure, the two terms are semantically equivalent. The SFR definition of the term is used for reasoning. The module flashes all the terms that are semantically same for this term. One term from a group of terms for the part can be selected for the required application. Schematic diagram of the process for identification of mismatch in terms/ labels for a product is depicted in figure 3. The proposed method for semantic interoperability of a product using SFR Framework is implemented using Protégé ontology editor [15]. Screen shot of different parts of SFR model is shown in the following sections.

6 Shape-Function-Relationship (SFR) ontology

The structure defined in section 5 is used to develop ontology of a product. Protégé ontology editor [15] is used to develop ontology for SFR (Shape- Function-Relationship) model. All terms are classified in terms of the criteria described in section 5. Figure 4 shows the class hierarchy with attributes and attributes' values for a product "Combustion Chamber". The parameters/ attributes that are associated with combustion chamber and used in the reasoning are shown in the right panel of the figure 4. Different terms associated with a part refer to the possible ways the part can be termed in different applications. The user defined term is a place holder for term/ label of a product and also for further extension of the SFR ontology to handle parts that are not defined.

Figure 4 The class hierarchy of the SFR model with attributes and attributes' values for "Combustion Chamber"



The attributes with their possible values of the shape, function and relationship elements are defined in table 6, table 7 and table 8 respectively. An example of each element is also described in the tables. Each attribute has a value from a set of predefined values. For example parameter "Velocity of fluid" in function element can be Decrease, Increase, Constant, Radial or Axial. The part with two terms can be identified by the reasoning module as both terms have same SFR structure. Two parts with single term/ name can be differentiated by the reasoning module as both parts have different SFR representations. Implementation to identify the mismatch in part terms/ labels among applications is described in the following sections.

Table 6 Attributes/ parameters and their possible values used to describe the Shape element.

Form	**Material**	**Parts**	**Product 3D model/ image**
FP1, FP2 … FPn	**MP1, MP2 … MPn**	**PT1, PT2 … PTn**	
Allowable values (String type)			
Product: Turbine shaft			
Cylindrical	MP1	Turbine shaft	

Table 7 Attributes/ parameters and their possible values used to describe the Function element.

Velocity of fluid	**Pressure of fluid**	**Temperature of fluid**	**Medium_in_contact**	**Motion of part/system**
Allowable values (symbol type)				
Decrease	Decrease	Decrease	air_in_air_out	Stationary
Increase	Increase	Increase	air_fuel_in_gas_out	Moving
Constant	Constant	Constant	gas_in_gas_out	Translation
Radial			air_in_contact	Rotation
Axial			gas_in_contact	
Product: Combustion Chamber				
Increase	Increase	Increase	air_in_gas_out	Stationary

Table 8 Attributes/ parameters and their possible values used to describe the Relationship element.

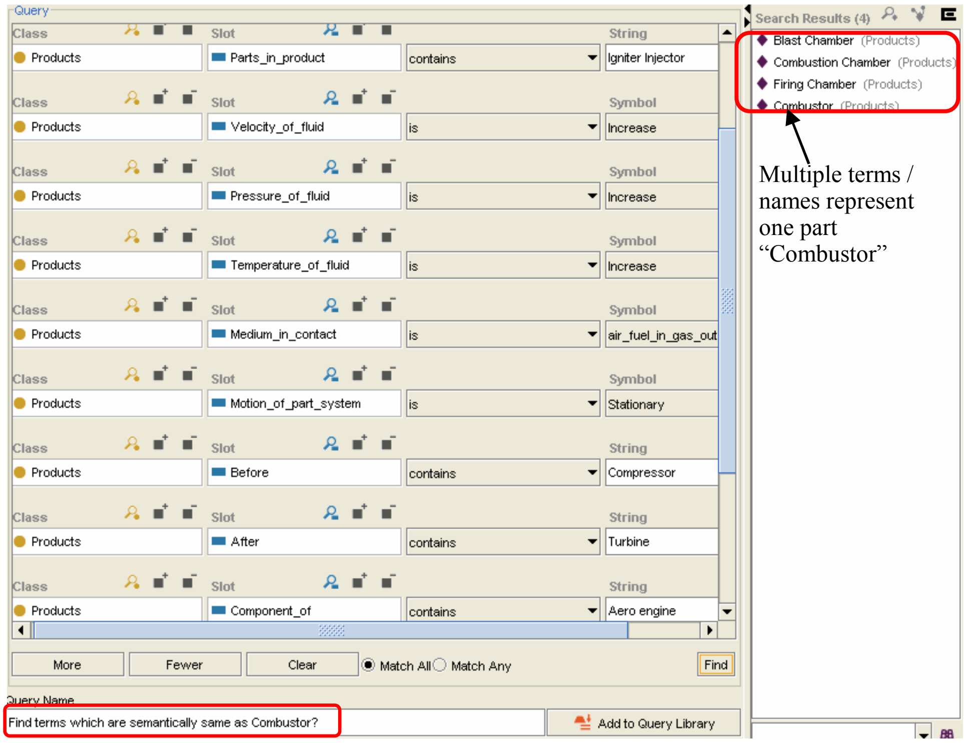
Before	**After**	**Component_of**
Product: Combustion Chamber		
Compressor	Turbine	Aero engine

6.1 Handling one part/ system (entity) has two or more names

The reasoning module shows multiple terms/ names are same as they have one SFR representation and therefore refer to one part. Figure 5 shows SFR representation (big left panel in the figure) of a "Combustor". The multiple terms which represent the same SFR representation as "Combustor" are shown in the right side panel of the figure. Thus the

SFR representation of a term in an application is used to i. find out equivalent terms for another application which represent the same part/ system or ii. Check if the given terms represent the same part or not.

Figure 5 Handling one part/ system (entity) has two or more names



6.2 *Handling two or more parts/ systems (entities) have one name*

A term representing two or more parts/systems will correspond to two or more SFR representations. The reasoning module is used to search multiple SFR representations for multiple parts referring to one term/ name (figure 6). User has to select an appropriate SFR representation for the term being used. For example "Compressor Blade" has SFR_A and SFR_B to represent "Rotor blade of a compressor" and "Stator blade of a compressor" respectively (figure 7). An interface is provided to visualize different SFR structures and to select an appropriate SFR structure for a particular application. The parts "Rotor blade of a compressor" and "Stator blade of a compressor" have some commonalities at higher levels of abstraction but the distinctions appear at the lower level. Context can be incorporated by clustering terms related to a particular application. Once a cluster is identified for an application then search with in the cluster becomes easy. This way search can be narrow down and handling of context can be brought in the reasoning.

Figure 6 Handling two or more parts/systems (entities) have one name

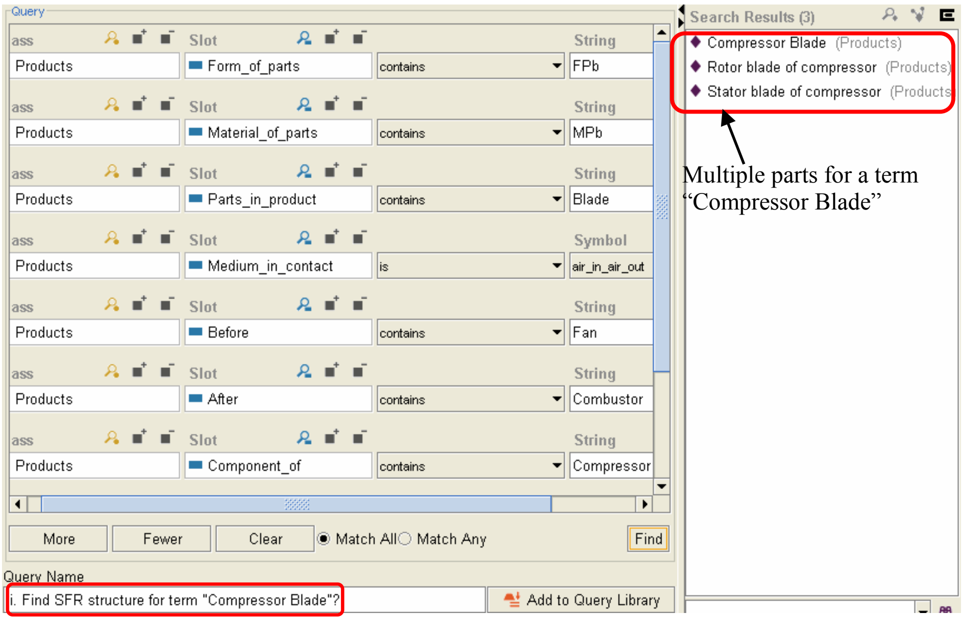
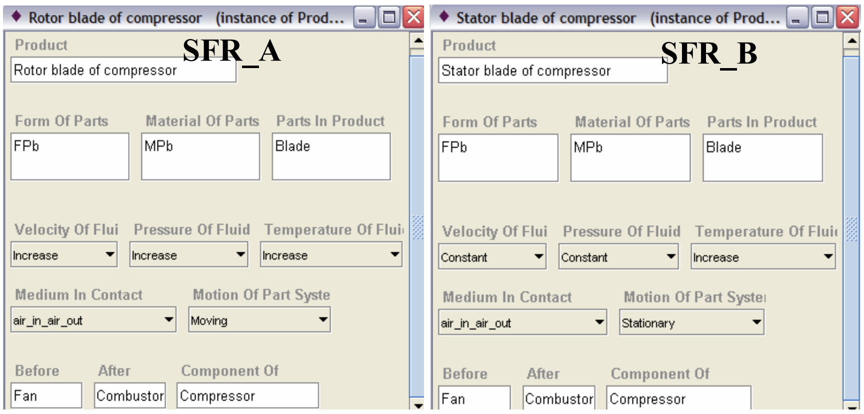


Figure 7 Multiple SFR representation for a tem "Compressor Blade"



7 Conclusions and future work

A taxonomy based on Shape, Function and relationship has been proposed to build an ontology that can be used to address semantic interoperability problem between different task domains. An ontology for the aero engine space has been developed and used to address mismatch of labels of parts between maintenance and design domains. Currently the ontology is constructed manually. Automatic means to extract the labels and build their representation in the SFR framework is being explored.

The work presented in the paper is a part of ongoing research. Ability of the SFR framework to uniquely describe the products in other domains is to be investigated next. Attempts are being made to build SFR based description for the machine tool domain. The authors are working on using the SFR model with IPPOP model [16] to explore use of product data to support decision-making. The authors are also working to combine SFR model with the core product model (CPM) [17].

References

1 Gupta, R.K., Gurumoorthy, B. (2008A) 'Extending feature based semantic interoperability for sheet-metal features', *International Conference on Trends in Product Life cycle Modelling, Simulation and Synthesis (PLMSS08)*, India.

2 Gupta, R.K., Gurumoorthy, B. (2008B) 'A Feature Based Framework for Semantic Interoperability of Product Models', *Strojniski vestnik – Journal of Mechanical Engineering*, Vol.54, No.6, pp. 446-457.

3 Patil, L., Dutta, D., Sriram, R. (2005) 'Ontology-Based Exchange of Product Data Semantics', *IEEE Transactions on Automation Science and Engineering*, Vol. 2, No. 3, pp. 213-225.

4 Mostefai, S., Bouras, A. Batouche, M. (2005) 'Effective Collaboration in Product Development via a Common Sharable Ontology', *International Journal of Computer Intelligence*, Vol. 2, No. 4, pp. 206-212.

5 Li, Z., Ramani, K. (2007) 'Ontology-based design information extraction and retrieval', *Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 21, no. 2, pp. 137–154,

6 Li, Z., Raskin, V., Ramani, K. (2008) 'Developing Engineering Ontology for Information Retrieval', *ASME Transactions Journal of Computing and Information Science in Engineering,* Vol. 8, no. 1, pp. 1-13.

7 Kim, S., Ahmed, S., Wallace, K.M. (2006) 'Improving document accessibility through ontology-based information sharing', *6th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2006)*, 18-22 Apr 2006, Ljubljana, Slovenia.

8 Ahmed, S., Kim, S., Wallace, K.M. (2007) 'A methodology for creating ontologies for engineering design', *ASME Transactions Journal of Computing and Information Science in Engineering,* Vol.7, no.2, pp. 132-140.

9 Kim, S., Bracewell, R., Wallace, K.M. (2008) 'Some reflections on ontologies in engineering domain', *7th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2008)*, 21-25 April 2008, Izmir, Turkey.

10 Nalluri, S.R.P.R. (1994) 'Form feature generating model for feature technology', *PhD thesis, Indian Institute of Science, Department of Mechanical Engineering*, Bangalore, India.

11 Subramani, S. (2005) 'Feature mapping, associativity and exchange for feature-based product modeling', *PhD thesis, Indian Institute of Science, Department of Mechanical Engineering*, Bangalore, India.

12 GKN Aerospace, (2008), http://www.gknaerospace.com/

13 Wikipedia, (2009), http://en.wikipedia.org/wiki/Turbofan

14 Autonomous System Lab, (2008), http://asl.epfl.ch/

15 Protégé, (2008) 'Protégé Ontology Editor', Stanford University, http://protege.stanford.edu/

16 IPPOP (Integration of Product, Process and Organisation for engineering Performance Improvement) is a French RNTL network project labelled by the French Ministry of Economy, Finances and Industry More information on http://ippop.laps.u-bordeaux1.fr/

17 Fenves, S.J., Foufou, S., Bock, C., Sudarsan, R., Bouillon, N., Sriram R.D. (2004) 'CPM2: A Revised Core Product Model for Representing Design Information', *National Institute of Standards and Technology*, NISTIR 7185, Gaithersburg, MD 20899, USA.