Development of an Ontology for a Multi-Agent System Controlling a Production Line

Nelson Ricardo Martins Rodrigues

Relatório Final do Trabalho de Projecto apresentado à
Escola Superior de Tecnologia e de Gestão
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para obtenção do grau de Mestre em
Sistemas de Informação

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Orientador:
Prof. Dr. Paulo Leitão

"Este Trabalho de Projecto não inclui as críticas e sugestões feitas pelo Júri".

Setembro de 2012

"Make everything as simple as possible, but not simpler."
Albert Einstein.

To my family, girlfriend and friends!

Acknowledgments

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I am deeply grateful to my parents, Eduardo and Alice and to my brother Tiago, which throughout my academic career and especially at this stage remained always supporters and motivators, for me to successfully overcome all the barriers. To my cousin Tiago that contributed for the success of the presented solution and to all my friends which directly or indirectly comforted me.

Finally for Mariana, the promise that I will try in the future to spend more time with her ;).

To all my thanks.

Abstract

Nowadays, the industry is very demanding in terms of customized high quality products at lower costs. Furthermore, the customers intention of having the product as soon as possible, and companies having the restriction of time, which in this case is a crucial variable, also increases the final product cost. For this reason, it becomes unacceptable the development of solutions based on centralized implementations, which do not provide robustness, flexibility and reconfigurability. Therefore, the implementation of multi-agent based solutions fulfil the described requirements leading to a more flexible, robust and agile system.

This work presents the development of an important issue concerning the cooperation between the distributed agents, since one of them only has a partial view of the system. In this way the ontologies are crucial to guarantee a common structure of the knowledge exchanged among the agents.

The objective of this work is the development of an ontology integrating process and quality levels to be used to represent the knowledge exchanged in a multi-agent system solution for a production line producing washing machines. Consequently, the agents exchanging shared knowledge will support better and more accurate decisions.

The contribution of this work comprises the implementation of a multi-agent system, the appropriate ontology formulation as well as its implementation, which makes the integration of an industrial production line more versatile and more customized. Naturally, with this project, it is created a reconfigurable and highly interoperable system.

Keywords: Ontologies, Multi-Agent System, Automation, GRACE.

Resumo

Hoje em dia, a indústria é muito exigente em termos de produtos personalizados de alta qualidade a custos baixos. Além disso, a intenção dos clientes é ter o produto logo que possível, assim as empresas têm uma limitação de tempo, que neste caso é uma variável importante, também aumenta o custo do produto final.

Por esta razão, torna-se inaceitável o desenvolvimento de soluções baseadas em implementações centralizadas, que não proporcionam a flexibilidade, robustez e reconfigurabilidade. Portanto, a implementação de soluções baseadas em multi-agente cumprem os requisitos descritos levando a um sistema mais flexível, robusto e ágil.

Este trabalho representa o desenvolvimento de uma questão importante relativa à cooperação entre os agentes distribuídos, uma vez que apenas um deles tem uma visão parcial do sistema. Desta forma, as ontologias são cruciais para garantir uma estrutura comum de conhecimento trocadas entre os agentes.

O objectivo deste trabalho é o desenvolvimento de uma ontologia da integração de processos e qualidade a serem utilizados para representar o conhecimento trocado em uma solução de sistema multi-agente para uma linha de produção de máquinas de lavar. Consequentemente, os agentes trocam conhecimento compartilhado que irão suportar decisões melhores e mais precisas.

A contribuição deste trabalho consiste na implementação de um sistema multi-agente, a adequada formulação da ontologia, bem como a sua implementação, o que torna a integração de uma linha de produção industrial mais versátil e mais personalizada. Naturalmente, com este projecto, é criado um sistema reconfigurável e altamente interoperável.

Palavras Chave: Ontologias, Sistemas Multi-Agente, Automação, GRACE.

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List of Acronyms

ACL	Agent Communication Language
AGV	Auto-guided Vehicle
AI	Artificial Intelligence
AP	Application Protocol
API	Application Programming Interface
BOM	Bill of Material
CNC	Computer Numeric Control
DAML	DARPA Agent Markup Language
EDI	Electronic Data Interchange
ER	Entity-Relationship
ERP	Enterprise Resource Planning
FIPA	Foundation for Intelligent Physical Agents
FOL	First Order Logic
GRACE	inteGration of pRocess and quAlity Control using multi-agEnt technology
GUI	Graphical User Interface

IGES	Initial Graphics Exchange Specification
JADE	Java Agent DEvelopment Framework
JESS	Java Expert System Shell
KIF	Knowledge Interchange Format
MAS	Multi-Agent System
MES	Manufacturing Execution System
NIST	National Institute of Standards and Technology
OIL	Ontology Inference Layer
OOP	Object Oriented Programming
OWL	Web Ontology Language
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
RDQL	RDF Data Query Language
RQL	RDF Query Language
SET	Standard d'Échange et de Transfert
SGML	Standard Generalized Markup Language
SPARQL	SPARQL Protocol and RDF Query Language
SQL	Structured Query Language
STEP	Standard for the Exchange of Product model data
SWRL	Semantic Web Rule Language

TOVE	Toronto Virtual Enterprise Ontology
UML	Unified Modelling Language
URI	Uniform Resource Identifier
W3C	World Wide Web Consortium
XML	Extensible Markup Language

Chapter 1

Introduction

Over recent years it has been noticed a strong pressure of markets demanding customized products with higher quality at reduced costs. The manufacturing industries are then forced to implement more intelligent, faster, modular, and flexible systems. Processes focused on agility, flexibility and re-configurability were applied in a distributed manner, leaving the traditional centralized ideology.

Nowadays, the implemented solutions are more intelligent, closer to the users, satisfying their needs in a more rapid and efficient way. These features make the implementation of production control systems more difficult, leading to a much more complex system.

The multi-agent systems (MAS) paradigm fits perfectly into the needs of a complex and adaptive system, where it is necessary to distribute such complexity, making the system more flexible, while maintaining or increasing the same robustness.

Due to its inherent characteristics, distributed and autonomous agents only have a partial view of the entire system, requiring the need to interact among them to exchange the shared knowledge. In this way, the use of ontologies is crucial to guarantee a common structure of the knowledge exchanged among the distributed agents during their conversations. With ontologies it is possible to properly share structured information without compromising the semantic issues that may exist. The sharing of information based on ontologies in a distributed system, produces an environment very easily malleable and with highly agile customization. Good base of knowledge representation of the factory line allows supporting better deciding making processes, have a fairly large impact because the system can adapt

or fix errors without the human interaction. Clearly, the decreasing number of errors will have a cost reduction for the manufacturing company, reducing the costs of production as well as time of bad production, since there are no delays caused by breakdowns and badly executed machinery. Due to easy communication and exchange of knowledge, agents have a better knowledge base to be able to decide more accurately. In this way, the MAS solution can create a distributed layer that provides intelligence and adaptation by distributing the decision-making processes along the line.

1.1 Motivation and Objectives

The motivation of this work lies in understanding how to develop ontologies and how to integrate, in a simple and easy manner in a multi-agent system. The opportunity to implement an ontology for a real industrial production line, under the European FP7 GRACE (inteGration of pRocess and quAlity Control using multi-agEnt technology) (www.grace-project.org) project, as well the problematic domain, makes this work interesting and challenging.

The main objective of this work is the development of an ontology, which integrates quality and process control for washing machines production line. This will be posteriorly integrated in a multi-agent system, which will control the production process in the production line. This thesis will handle the corresponding reports of the design processes.

The described objective will comprise three main sub-objectives. The first sub-objective is associated with the study of the state of the art related with the existing ontologies, practices, languages and tools that are used to help on the development and integration of ontologies. Brief discussions of multi-agent systems and existing ontologies in a manufacturing field will be made.

The second sub-objective is related to the design of the ontology schema, which requires the identification of the domain concepts, their attributes, the relations among concepts and relations to the associated restrictions and attributes. The validation of the designed model and is mainly performed by the instantiation of practical examples.

The third and final sub-objective is related to the integration of the designed ontology schema in a MAS solution.

During the design and implementation of the system and also the ontology model, it was

possible to present and validate these concepts by some articles published on international conferences. Also during this stage some deliverables for the GRACE project have been wrote.

1.2 Limitation of Scope

As referred, it is crucial a design of an ontology to deliver a common understanding on the vocabulary used by the intelligent, distributed agents during the exchange and sharing of knowledge. In order to control the concepts of the domain, the ontology range was restricted. In this way, it is necessary to keep in mind that the terms and concepts used to construct the ontology, can in another point of view, create different meanings and thus a different ontology at the end. The ontology created might not be unique, but the objective is not to create a generic solution, which can be used as several solutions for different problems, but a conceptualization for the washing machines production lines case study.

The ontology design was thought taking into consideration only the integration with multi-agent systems, and not in the ontological philosophical subject, neither in a semantic web purpose.

The development of the multi-agent system infrastructure is not the main issue of this topic and it is only the recipient of the ontology development and will be used to test the conversation among the agents using the developed ontology to represent the exchanged shared knowledge.

1.3 Document Organization

The document is divided into 7 chapters. After this brief introduction, chapter 2 will provide a contextualization of the ontologies to address the knowledge representation and the interoperability in distributed, heterogeneous systems. Also it gives an overview about the methodologies and available languages to develop ontologies and the existing ontologies for the manufacturing domain. In Chapter 3, it is described the application domain and briefly explained the domain that will be modelled. Chapter 4 describes the specification and implementation of the multi-agent system infrastructure using the JADE framework. Chapter

5 is devoted to the design of the GRACE ontology schema for production line systems, integrating process and quality control, describing very briefly the main concepts, predicates, attributes and restrictions, and elaborating a validation of the GRACE ontological model by instantiating the ontology schema. Chapter 6 presents the integration of the designed ontology in the implemented multi-agent systems infrastructure. Finally, Chapter 7 discuss the conclusions achieved during the development process and points out some possible future work. Additionally, two annexes detail the description of the GRACE ontology and the frameworks available to develop agent-based solutions.

Chapter 2

Ontologies for Multi-agent Systems

The communication among distributed agents requires a common understanding of the exchanged knowledge during the conversation. For this purpose, terminology of the conversation has to be dominated by the agents in such environments, the knowledge of each agent must be specified for a particular domain, labelled by concept of *ontology*.

In this way, ontologies always end up being necessary to support the understanding within multi-agent system. In the case of distributed computing systems like MAS there must be some kind of consistency in the conversation of the actors involved.

This chapter discusses just that, the integration of these two worlds. First, will be introduced the MAS paradigm and its application to manufacturing systems. After that, a theoretical overview of the ontologies is presented. Also is providing some notions, identifying particular components and recognize types of existing ontologies. Then, it is addressed the design and development phases of an ontology, referring the main issues, tools and ontology languages. At the end, the chapter surveys the existing ontologies for the manufacturing domain.

2.1 Multi-Agent Systems

A multi-agent system is composed by many intelligent and autonomous agents, which have the ability to communicate with each other to reach faster or with more precision to a common

goal. On the following sections these subjects will be presented with more deeply detail.

2.1.1 Definitions

The multi-agent systems paradigm result from the Distributed Artificial Intelligence (DAI) field [88],[18]. The concept of agent is neither unique nor consensual, mainly because some attributes are more important than others. Some proposed definitions found in the literature are summarized below:

- an agent is "*an autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it doesn't possess knowledge and skills to reach alone its objectives*" [46].
- "*an agent is a computer system that is situated in an environment and that is capable of autonomous action in this environment in order to meet its design objectives*" [88].
- *"an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors"* [72].
- *"an agent is a computational entity that can be viewed as perceiving and acting upon its environment, that is autonomous and that operates flexibly and rationally in a variety of environmental circumstance"* [91].
- *"an agent is a persistent computation that can perceive its environment and reason and act both alone and with other agents. The key concepts in this definition are interoperability and autonomy"* [75].

Agents have diverse characteristics, such as intelligence, autonomy, pro-activeness, adaptation and social behaviour. All of them are important, but depending on the objectives, their importance can increase or decrease. In multi-agent systems, autonomy and cooperation have a special prominence. The autonomy can be represented as the ability to perform their own decisions without human intervention; autonomy allows systems to perform in dynamic environments; different levels of autonomy can be specified. Cooperation is the capability to interact with each other, acting together to achieve a global system goal, or shared goals.

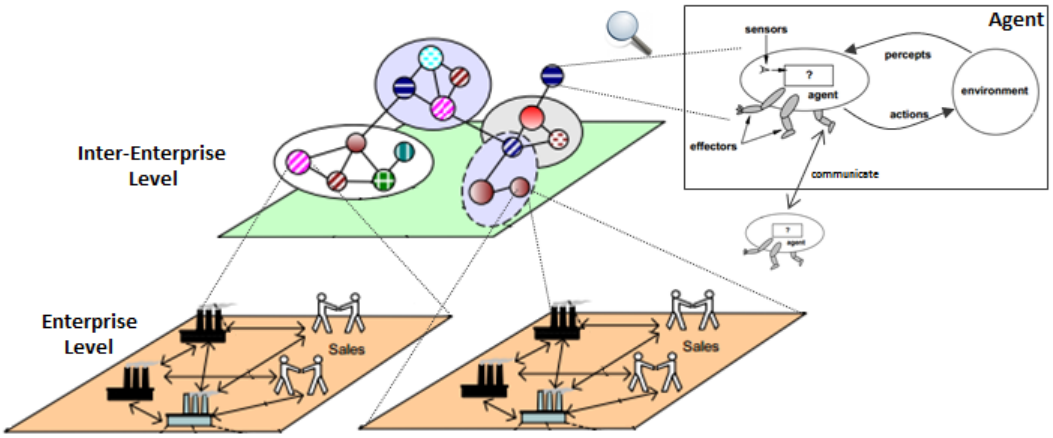

Figure 2.1: *Top and bottom view of the agents (adapted from [46]).*

A multi-agent system is a society of agents that represent the physical and logical objects of a system. The global system behaviour is achieved through the collaboration and interaction among the individual agents, each one having its own objectives and behaviours, and possessing its own perceptive and cognitive competences. In multi-agent systems, each agent has only a partial view of the system. The development of an agent-based control system usually follows a bottom-up perspective.

This paradigm introduces several advantages when comparing with the traditional approaches. For instance, more robust solutions are realized since a multi-agent systems solution distributes the control functions over agents' networks, thus some of the critical failures, like bottleneck problems, which are mostly associated to centralized systems, no longer exist.

2.1.2 Agent Oriented versus Object Oriented Programming

A common misunderstanding is the confusion between AOP (Agent-Oriented Programming) and OOP (Object Oriented Programming). In spite of several similar issues, these two approaches are different. First, the agents can be implemented with an object oriented language (e.g. C++ and Java) but also using a non-object oriented language (e.g. C or Lisp).

The second difference lies on some aspects of being autonomous. The object has some

functions, which were created to be executed when requested, without any decision. Comparing with the agent, that has some skills to execute, this is different because the agent can think what is better to him-self and refuse that order of task execution.

Several methodologies were introduced in the literature to support the specification and engineering of multi-agent systems, such as AALAADIN [19], Tropos [9], Prometheus [68], Agent UML [6], and GAIA [87], the last one probably being the best known methodology. These methodologies have their principles on object-oriented programming, and present some limitations, namely: they do not deal directly with particular modelling techniques and with implementation issues. Particularly, and as sustained by [38], GAIA does not present a holistic model of the execution environment to the developers, which renders inappropriate for engineering applications with dynamic and heterogeneous environments.

2.1.3 Application Domains

The multi-agent systems technology is being applied to different domains. In literature, it can be found several examples of agent based solutions, for example in the market trading, telecommunications, healthcare, movies (e.g. in the "The Lord of the Rings", the agent technology was used to model individual fighters). As other examples, Whitestein Technologies developed an agent-based solution for automatic optimisation for large-scale transport companies and, Aerogility and Rolls Royce companies have been developed an application to reduce the complexities of the aerospace aftermarket. IBM is also using agents to support its autonomic computing systems to increase their productivity and DaimlerChrysler implemented a solution on their factory floor using agents. In the aerospace field, NASA a agent-based solution to balance multiple demands on its satellites. This and others industrial applications of multi-agent systems can be found in [54][90].

2.2 Ontologies

An ontology is an agreed model, within a conceptualization of the domain of interest. An ontology allows the definitions of the vocabulary in a richer manner that will support the knowledge description, allowing restrictions on their features and properties.

Compared with the taxonomy[1], ontologies represent a higher and more flexible level, and can define the semantics of the terms of a vocabulary, concepts and relations of interconnected terms [13]. In this chapter some ontology terms and definitions will be presented.

2.2.1 Definitions

The term ontology has been gradually used due to the need to represent knowledge in a particular area, and has gained more interest with the Semantic Web advent.

The term ontology is vague and not precise. Among the several definitions of ontology that can be found in the literature, the following ones can be pointed out:

- An ontology "*defines the basic terms and relations comprising the vocabulary of a topic area as well the rules for combining terms and relations to define extensions to the vocabulary*" [61].

- An ontology is "*a formal, explicit specification of a shared conceptualization*" [29]. In this definition the terms used have the following meaning:

  - "Formal" refers to the fact that the ontology should be machine readable.
  - "Explicit" means that the types of concepts used, and the constraints on their use, are explicitly defined.
  - "Shared" reflects that the ontology should capture consensual knowledge accepted by the communities.
  - "Conceptualization" refers to an abstract model of phenomena in the world by having identified the relevant concepts of those phenomena.

- An ontology is "*a logical theory accounting for the intended meaning of a formal vocabulary, i.e. its ontological commitment to a particular conceptualization of the world*" [32].

[1] A taxonomy is a terminology in which the terms are organized hierarchically. Each term can share a relationship between a parent and a child node (specialization / generalization) with one or more elements of the taxonomy.

- An ontology "*provides meta-information which describes the data semantics, being possible to represent knowledge and use that knowledge to communicate with various types of entities (software agents or humans)*" [17].

- An ontology can be described as "*means of enabling communication and knowledge sharing by capturing a shared understanding of terms that can be used both by humans and programs*" [44].

In spite of all the different definitions, it is consensual that an ontology creates shared understanding, enabling the exchange of knowledge and the capability to reuse that knowledge. In other words, an ontology defines the vocabulary and the semantics that are used in the communication between distributed entities, and the knowledge relating to these terms.

In the computational world, ontologies are one way to describe computationally processable knowledge, but also to increase communication between computers and humans. There are three main reasons for using ontologies [79], namely:

1. Assist in communication between humans and computers.

2. Achieving interoperability between software systems.

3. Help improve the quality of design and system architecture software.

A pertinent question is the difference between ontologies and databases. Both ontologies and databases provide a way to store data in a structured way. But ontologies do more, by providing the capability for the formal description of data and rules about their context, instead of a static way to store knowledge. As consequence, ontologies allow to deal with incomplete data, to infer answers from current ontology data and to reveal contradictions/inconsistencies. In such way, databases are considered when: i) the schema is small and simple, and ii) all information is available and was not created due to a query. On the other hand, ontologies are considered when: i) the schema is large and complex, and can be created at query time, ii) it is possible to infer answers (i.e. query answers reflect the schema and the instances/data), and iii) it is necessary to deal with incomplete information.

Table 2.1, summarizes the several differences between database and ontologies.

Table 2.1: *Differences between Databases and Ontologies* [78].

	Database	Ontologies
Focus	Data	Meaning
By the way	Meaning Lost	Instances optional
Notation Syntax	ER diagrams	Logic
Notation Semantic	Minimal focus on formal semantic	Strong focus on formal semantic
Expressivity overlap	Entities	Classes
	Attributes, Relations	Properties
	Constrains	Axioms
Expressivity differences	Constrains for integrity	Constrains for meaning
	Foreign key	Consistence and Integrity
Starting Point	Scratch	Reuse if possible
Processing Engines	Reasoning with Views	Derive new Information from existing information

Another comparison to ontologies that is made quite often is with OOP, because of the use of similar terms, like classes and attributes. As like what happens in OOP languages, the advantage of using classes, which defines a small domain, is the reuse of the same class for a variety of activities, this is similar to what happens with the ontologies. But there are some differences, ontology technology is more theoretically found on logic when comparing to OOP also ontology allow inheritance of properties, the object-oriented modelling does not. Other differences can be found in [86].

2.2.2 Components

There are different terminologies to describe correctly an ontology. Because of the diverse derivations and possible solutions to implement the ontology, it is mandatory to pass through a solution using RDF (Resource Description Framework), due to several reasons:

- It is a W3C standard understood and accepted by the community.
- It supports the most simple sentences as well as the resolution of most complex problems with inference.

- It is very used by the Semantic Webs communities.

The basics of the RDF is illustrated in Figure 2.2.

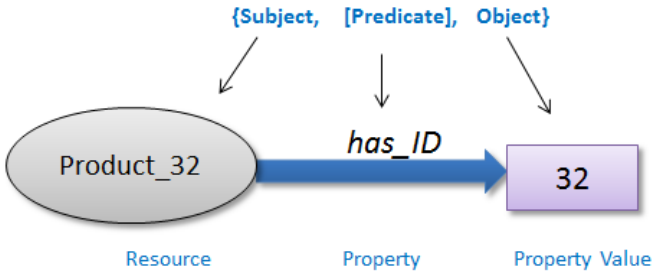

Figure 2.2: *Main ontological components using RDF Language.*

As illustrated in Figure 2.2, the three main components are the Subject, Predicate, and Object. From the left to right it can be seen the first resource, the subject. The arrow always has a direction and an associated predicate, always pointing to the object, these concepts represent a triple. An ontology is formed by several of these triples. These sentences may be combined, in a manner that the same term could be an object in one sentence, and in another sentence representing the subject. In more detail:

- **Subject**: must be a unique name that represents very well the element described (similar definition is the term Class).
- **Predicate**: represents the binary relation, between two concepts.
- **Object**: is the term that represents the value of the subject.

The previous points represent terms of the RDF language, but when it is developing the ontology the conceptualization is made in the following terms:

- **Classes** represent the concepts of a model, when modelling a domain classes are the first thing that is thinking. The idea is to create some kind of hierarchy between them. Any resource that can be characterized, for example: person, book, colour, any conceptual object that can be used to specify a specific domain.

- **Attributes** are used to characterized a concept Data Type, because those values represent only a pre-defined data, like a string, integer, Boolean, etc.
- **Relations** are used to make an association between two resources, i.e. the predicate from RDF language. A relation has a domain, which is the first concept, and the second is the range. In this case the range is not a Data Type, but another concept.
- **Instances** are individuals created to specify an object of a class.
- **Triple** is called from the combination of the previous concepts {subject, predicate, object}.

2.2.3 Methodologies

The development of ontologies has a strong derivation from the object-oriented design, presenting some difficulties, namely the manual construction, reuse and definition of concepts. When it is necessary to start modelling an ontology of any domain in concrete, the most common way always to think as an abstract concept, and then specializing each time it is opportune to improve in details. Figure 2.3 illustrates an example, by analogy.

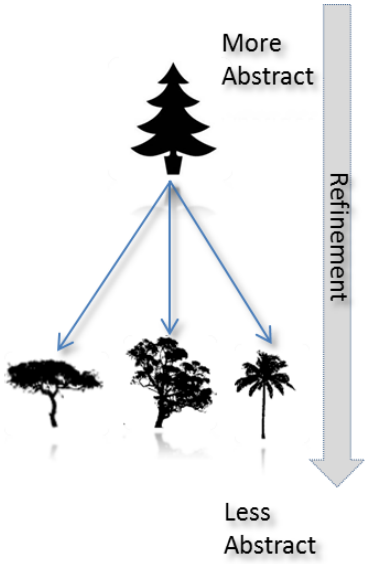

Figure 2.3: *Example of a ontology concretization.*

Here it is represented on the top, the normal and common tree, i.e. the most possible abstract one. It starts to be more characterized passing through some refinements and then reaches to a concrete tree. This is the normal approach and some of these concepts are implemented in OOP languages. In ontologies, when it is necessary to model some domains, these approaches can be more detailed. To help on this specification it is possible to follow some guidelines.

Noy and McGuinness propose a methodology for the development of ontologies, illustrated in Figure 2.4, comprising a set of stages to be fulfilled [63].

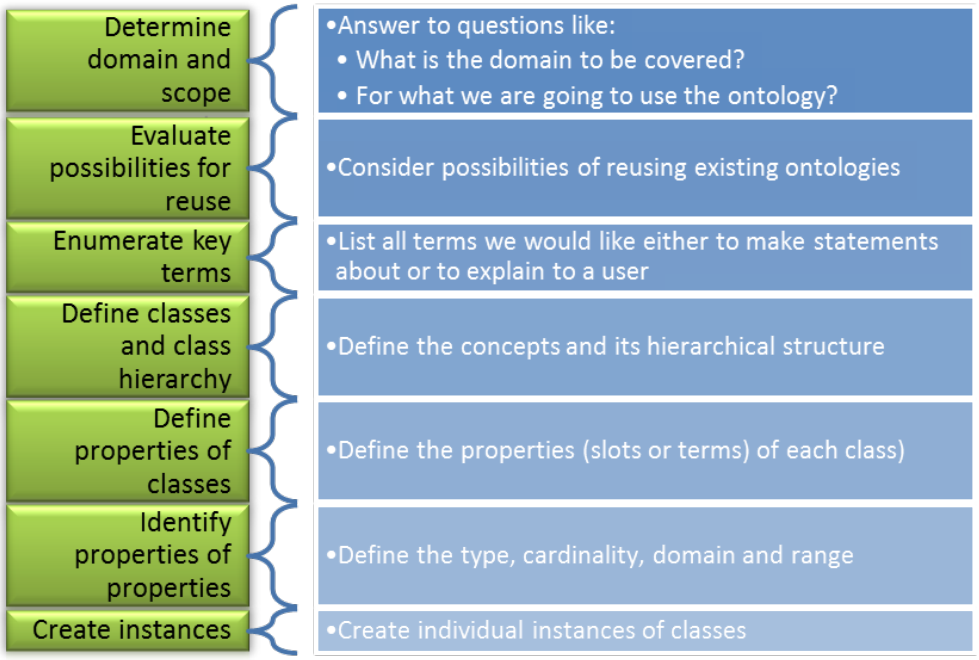

Figure 2.4: *Methodology to build ontologies proposed by Noy and McGuinness [63].*

The main idea in the development process of an ontology is to verify if existing ontologies can accomplish the proposed requirements, aiming to reuse ontologies. If the requirements are not accomplished, the option is to move to the next phases of the Noy and McGuinness methodology. Although, this is one of the most used approaches from who develops ontologies, Gruber proposed some principles to define ontologies, namely [30]:

- **Clarity**: the terms used in the ontology must be clear for those who read and must be

readable independently of the social situation or computational situation (implementation independent).

- **Coherence**: the ontology should avoid doubts and misunderstandings about the terms used.

- **Extensibility**: the ontology design should support an easy expansion of the shared vocabulary.

- **Minimal encoding bias**: the design must be conceived in a particular level independent of symbol-level encoding (note that agents sharing knowledge can be implemented in different systems and using different languages).

- **Minimal ontological commitments**: the ontology must demand a minimal ontological compromise in order to support shared activities.

The process for the design of an ontology accounts with the contribution of different entities, each one being expert in its own domain [40]. The entities involved in the ontology development process, as illustrated in Figure 2.5, are:

- **System developers**, which are responsible to provide the technological tools to support the development of the ontology.

- **Ontology engineers**, which are responsible for the design and implementation of the ontology.

- **Domain experts**, which are entities that don't understand the technology to develop the ontology but know reasonably well the knowledge on their domain.

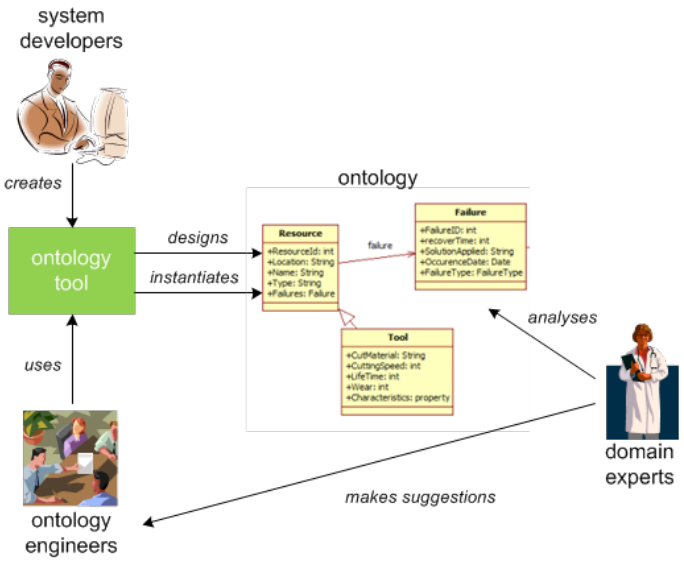

Figure 2.5: *Roles of entities involved in the ontology design.*

The ontology architecture is then developed by the ontology engineers according to the suggestions of the domain experts.

2.2.4 Types of Ontologies

In the literature it is possible to find diverse forms to represent the knowledge, classified according to different levels of formality [80]:

- **Highly informal**, i.e. expressed in natural language.
- **Semi-informal**, i.e. expressed in a structured form of a natural language.
- **Semi-formal**, i.e. expressed in an artificial and formally defined language.
- **Rigorously formal**, i.e. expressed with precise terms, formal semantic.

Another classification form, belongs to [34], where they distinguish three main categories, focusing on the level of granularity:

- **Terminological ontologies**, which are made of lexicons that specify the terminology which is used to represent knowledge.
- **Information ontologies**, which defines the structure of a database.
- **Knowledge modelling ontologies**, specify conceptualisations of the knowledge.

According to [32], it can be also considered the type of generality that is modelled, represented in Figure 2.6 (the arrows represent specialization relationships):

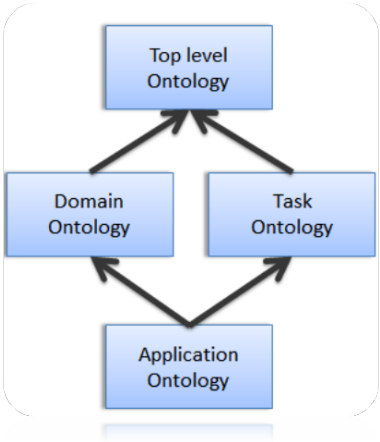

Figure 2.6: *Ontologies generality according to their level of dependence.*

- **Top-level ontologies**, that can be defined as the most abstract kind of ontologies because describes very general terms, and it is not a specification of a particular domain, by the contrary.
- **Domain ontologies**, that provide information, a vocabulary related to a generic domain like automation, medicine and others.
- **Task ontologies**, that provide concepts related to a generic task or activity such as, execute, perform operation, selling, and make a diagnosing between others. This is an extension of the top-level ontologies because the idea is to specialize terms that were introduced in to top-level ontologies.

- **Application ontologies**, that provide terms inherited from domain ontologies and task ontologies, it is very easy to think in this concept as "roles", where domain ontologies have the domain term, and task ontology has the activity.

In this work can be considered that the ontology developed belongs to a domain ontology, which is manufacturing domain, taking into special attention to task ontologies, because the ontology predicates mixed with the agents' behaviours can be easily compared. In terms of formality it can be pondered in a semi-formal language.

2.2.5 Ontology Languages

Ontologies could be developed by using a wide range of knowledge representation techniques. KIF (Knowledge Interchange Format) is a language that allows a user to develop ontologies, based on the first-order logic (FOL). It allows the inter-operation of agents with different knowledge bases, through the translation of each knowledge base into the KIF format, which will be shared. When an agent receives a knowledge base in KIF, it converts the data into its own internal form; when the agent needs to communicate with another agent, it maps its internal data structures into KIF.

Ontolingua [16] is the best-known KIF ontology, intending to provide a common platform in which ontologies developed by different groups can be shared [87]. Ontolingua consists on:

- A library of ontologies, expressed in the Ontolingua ontology definition language, which is based on KIF.

- A set of tools for editing and analysing the ontologies.

A set of translators for converting Ontolingua sources into forms acceptable to implemented knowledge representation systems.

Nowadays, there are several languages to describe ontologies, but the most used language is OWL (Web Ontology Language), which was inherited from XML.

The Resource Description Framework (RDF)[45] is another language used to develop ontologies based on the markup languages, e.g. the Standard Generalized Markup Language (SGML) and the eXtensible Markup Language (XML). Since XML is a declarative language,

being quite limited, RDF appears to overcome these limitations, e.g. in terms of relations. RDF is used for representing information about resources on the web, thus constituting a basic ontology language. In RDF, the statements used to describe resources are represented as triples, consisting of a subject, predicate and object, i.e. {S, P, O}.

The RDF S (Resource Description Framework Schema) is a semantic extension of RDF, namely by extending the RDF vocabulary to allow describing taxonomies of classes and properties, supporting the demand to create a schema. It provides mechanisms for describing groups of related resources and the relationships between these resources. These resources are used to determine characteristics of other resources, such as the domains and ranges of properties.

The Web Ontology Language (OWL)[84] mentioned above is another markup language that semantically extends RDF and RDFS is derived from the DAML + OIL (DARPA Agent Markup Language - Ontology Inference Layer)[36]. OWL has a rich set of modelling constructors, offering improved pre-defined templates, e.g. supporting the inclusion of restrictions in the concepts and predicates. Note that none of the other previous languages offer this kind of feature. Additionally, OWL provides a more expressive manner to represent knowledge, i.e. it is possible to define a model with more and better semantic value. This allows to overcome the lack in Unified Modelling Language (UML), since in UML it is not possible to represent this as clearly expressive as in OWL.

Figure 2.7 illustrates the evolution of markup languages used to express ontologies, since the SGML to OWL.

Figure 2.7: *Evolution of the markup languages.*

Other techniques can be used for the knowledge representation, namely UML, used in software engineering and ER (Entity-relationship) diagrams, used in databases. These techniques allow a different modelling perspective due to the high abstraction level.

The selection of the proper language to formalize the structure of the knowledge should take into consideration some important issues. The first one is that artificial intelligence based languages (i.e. KIF and markup languages) are better suited to represent and implement

ontologies than UML and ER diagrams, allowing to introduce more semantically descriptions. Secondly, languages based on XML are better suited to support the exchange of ontologies between applications. At last, from the set of markup languages, the OWL is the one that provides the most diverse capabilities for description because it has all the characteristics of a markup language and also the reasoning layer that allows representing an ontology in a more expressive manner.

2.2.6 Frameworks the Management of Ontologies

The development of ontologies is a complex task that requires the support of proper frameworks which assist the creation or manipulation of ontologies and are able to express ontologies in one of many ontology languages.

Examples of relevant criteria for choosing an ontology editor are:

- The degree to which the editor abstracts from the actual ontology representation language used for persistence.
- The visual navigation possibilities within the knowledge model.
- The incorporation of methodologies and languages, in an easy way.
- The ability to import and export foreign knowledge representation languages for ontology matching.
- The licensing costs of the ontology editor.

The use of these tools may lead to an easier ontological learning and also a more productive task in the design of ontologies, supporting the concurrent work of the ontology engineers and the domain experts.

Several frameworks are currently available, namely OntoEdit [76], WebODE [14], Protégé [24] and Hozo [41].

OntoEdit, based on CommonKADS [73], is an ontology editor that has been developed to support the development and maintenance of ontologies through a methodology-guided approach. It provides the capability to develop ontologies with the help of inference and be

extensible through a plug-in structure. Figure 2.8 illustrates a screenshot of the OntoEdit tool.

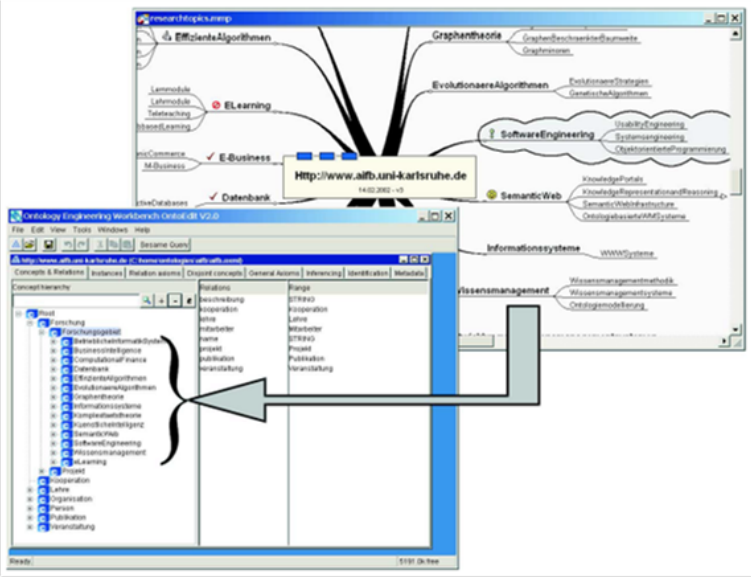

Figure 2.8: *Screenshot of the OntoEdit editor.*

This tool permits the fast development and the possibility to perform different levels of analysis, supported by the graph schemas visualization. OntoEdit is very widely used for reasoning and evaluation phases, and can be used also in online mode.

WebODE is a scalable, extensible and integrated workbench that supports the ontology development process, allowing the design of the ontology by levels, creating different layers that decrease the complexity of the process. The integrated workbench is based on the ontology development methodology METHONTOLOGY. WebODE was one of the first tools for developing ontologies allowing the persistence of the data in Microsoft Access databases. Figure 2.9 illustrates a screenshot of the WebODE tool.

Protégé is probably the most used tool for the development of ontologies, either for developing from scratch, and merging, importing, querying and export of ontologies. It is a free, open-source platform, under the GNU license, which provides a suite of tools to construct domain models and knowledge-based applications with ontologies. In Protégé it is possible to create ontologies based on different types of expressiveness, being perfect for modelling

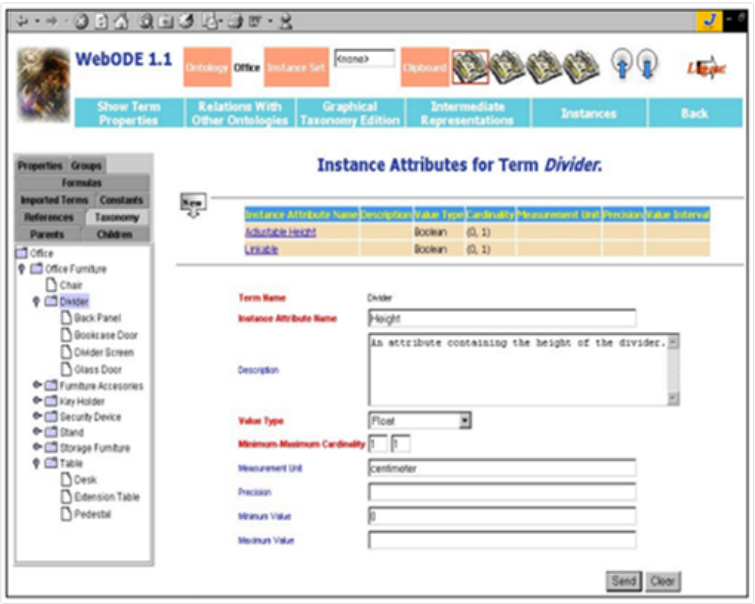

Figure 2.9: *Screenshot of the WebODE editor.*

a knowledge environment by using the Noy and McGuiness methodology [63]. Additionally, there are many plugins to be used with Protégé, e.g. to support the validation phase and to export the ontology in different formats (OWL, RDFS, RDFS, XML). Figure 2.10 illustrates a screenshot of the Protégé tool.

In this work, Protégé will be used to edit and verify the ontology correctness, since it is a free platform and it provides all necessary characteristics to support a suitable abstraction and technical implementation of the GRACE ontology in a graphical manner.

KAON2 is a Java-based framework that allows the manipulation of ontological concepts; this framework was created by Karlsruhe University together with the University of Manchester. Looking at the architecture of this framework it does not seem to be complicated. It hides some of this complexity on the TBox and Abox models. It also permits the importation of relational databases, Semantic Web Rule Language (SWRL), inference engines and it can export to various formats. One known problem of Kaon2 is that cannot handle large numbers in cardinality statements. In the current project that is a problem, because the ontology schema has various cardinalities.

The JENA framework [37] is a well-known tool in the academic world due to the fact

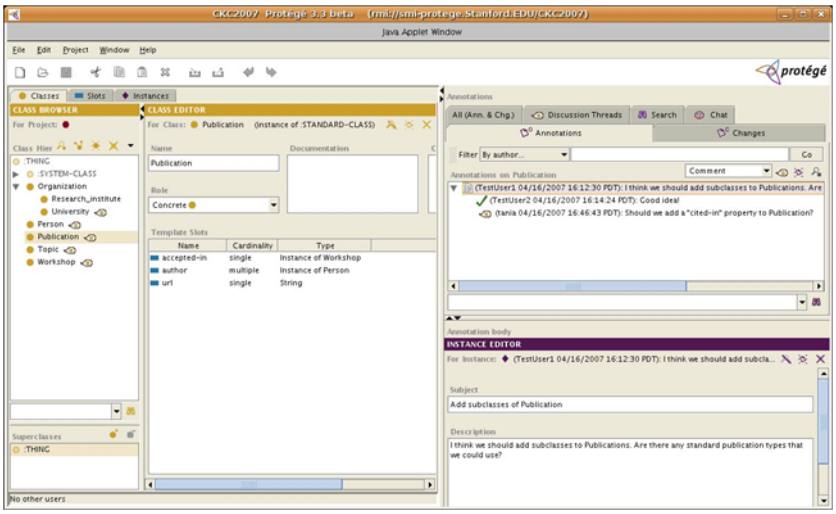

Figure 2.10: *Screenshot of the Protégé editor.*

of being able to handle the ontological models perfectly, and having a great manipulation capacity. It was developed in the HP laboratories, and it is based on JAVA providing an API for working with RDF, OWL, DAML + OIL. Michael Grobe [28], was one of the pioneers on the development of this tool.

Even the Protégé API can be used just like the KAON2 or JENA. This API is implemented in Java and is essentially the same as Protégé, only without the graphic component. This API is to be used in conjunction with JENA because the construction is based on the protégé JENA.

2.2.7 Combining Ontologies and Multi-agent Systems

In collaborative distributed environments, a common understanding of the shared knowledge is required to guarantee their interoperability. Just like the multi-agent systems are characterized from being distributed and heterogeneous, each agent needs to communicate to other agent in order to perform their goal. It does not matter if the goal is individual or global, if communicating with other agents helps, then they need to talk the same language to be understandable. This means that agents need to understand the terminology of the agents involved in the communication, see Figure 2.11.

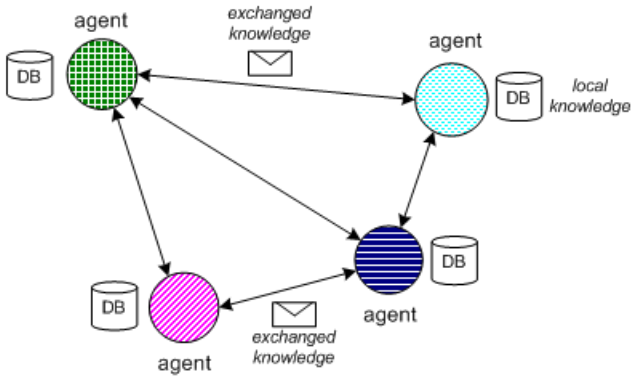

Figure 2.11: *The need of exchange shared knowledge in distributed systems.*

Analysing the Figure 2.11, it can be seen the interaction between the agents, and the message with some kind of knowledge exchanged, in order to agent understands the terminology that is on the content message, that he received. There must be some agreed coordination among the agents. It is necessary to create a strategy in order to create a common language, creating proper mechanisms to share the knowledge structure, this approach will lead the agents to a unique structure.

Ontologies helps on the creation of these structure, apart from creating a more expressive and more meaningful message, it's also creates a message that will share the structure agreed by the agents. The solution is to use proper mechanisms or techniques that guarantee the mutual understanding among the distributed entities, on this project ambit, the references to distributed entities are the agents that form the multi-agent system. Making a simple analogy, imagine a meeting with attendees coming from different countries and speaking different languages, it is necessary to find a common language, like a standard.

The agent's interaction is supported by the exchange of messages, as it was shown before. This interaction is founded using Agent Communication Language (ACL), which pretends to transform the messages exchanged more interoperable.

The two major agent communication languages are KQML (Knowledge Query and Manipulation Language) [21] and FIPA-ACL (Foundation for Intelligent Physical - Agent Communication Language) [42]. These specifications, KQML and FIPA, are very similar, they both deal with the messages in order to achieve a mutual understanding of exchanged mes-

sages using speech act theory [74]. The KQML is the first best-known language due to the fact that is the first that emerged, compared with FIPA. At its foundation it supports two different contexts, a formalization of the message format and a message-handling protocol [21], [18].

The FIPA protocol offers something more, such as protocols. That intends to describe different interactions. FIPA consequently provides several protocols of interactions, each representing different conversation acts, such as requests, information and so on. A quite usual protocol is contract-net, which provides the interactions in the conversation between sellers and buyers [42]. Both specifications are similar in some aspects and different on the concepts, actually FIPA-ACL uses layers of KQML and adding one more, to provide a more transparent layer of conversations among the agents. Figure 2.12, represents one example of a FIPA conversation in this case using a Query performative.

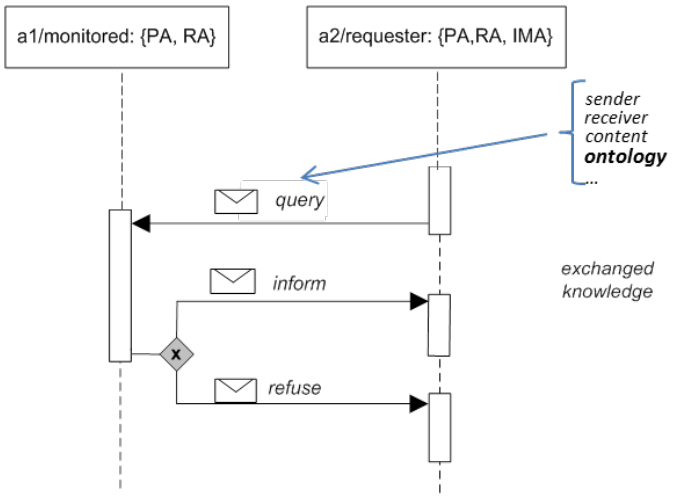

Figure 2.12: *Example of a conversation using the ontology and the Fipa Protocol.*

This kind of conversations can became more and more complex depending of the amount of agent's interaction. The Figure 2.12 contains a conversation between two agents (a1, a2), where the receiver agent (a1) receives messages which contains several message characteristics, such as the identification of the agent that sends the message, the receiver agent, the ID of the conversation, the identifier of the ontology, the contents of the message, among others characteristics.

2.2.8 Existing Ontologies for Manufacturing Systems

Ontologies are used in several domains, among others in the manufacturing field, which is the domain of this work. This can be confirmed in [65] and [66], which refers that the ontologies are currently used on agents to act as knowledge-base. In the literature, several ontologies addressing the manufacturing domain were proposed in the last years by the research community.

The EU FP6 PABADIS'PROMISE (Plant Automation based on Distributed System Product Oriented Manufacturing Systems for Re-Configurable Enterprises) project proposed a reference meta-ontology for manufacturing [20]. This ontology is very generic where each definition attempts to be more abstract and wide-ranging, covering a bigger domain. ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems)[47] defines an ontology for manufacturing control domain, which was formalized with the DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) language [8].

MASON (Manufacturing's Semantics Ontology) introduces an ontology with the same objectives, but is expressed with the OWL language in order to unify the ontologies using cognitive architectures, leaving to an implementation of a generic manufacturing ontology [50].

Other attempts to establish generic manufacturing ontologies are the NIST's description of shop data model [56], the Automation Objects [67], OOONEIDA focusing on the infrastructure of automation components by applying the semantic web technologies [83], and TOVE (Toronto Virtual Enterprise Ontology) that describes an ontology for virtual enterprise modelling [22]. The ISO 15926 standard [5] aims to support the integration of industrial automation systems, being developed by an ontology taking into account diverse variables, including the space and time.

An ontology for decentralized production control based on standard ANSI / ISA-95 was developed to work with Web services [26]. Some of the most used items and methods chosen on the creation of a manufacturing ontology, are described in [89]. The creation of an architecture using SOA (Service-Oriented Architecture) on industrial machinery was developed, taking in consideration the manufacture process management system based on the use of ontologies [55]. Inside of the PABADIS'PROMISE's domain a project was developed [77] to

turn more interoperable the languages to agent's interaction. Concept for seamless interaction in a distributed heterogeneous manufacturing environment was solved with a common ontological model. A more theoretical project is concerned with the connectionism [15], how it was achieved to an ontological solution that fixed the problems in a manufacturing domain, how are made the ontological connections between entities. A methodology to enforce the relation between MES (Manufacturing Execution Systems) and shop-floor control was established using meta-ontologies and one of the multi-agent system methodologies, namely GAIA approach [25]. It was proposed on [23] a manufacturing navigation platform, which allow the ontology-based process modelling and the ontology generation support by text mining. Protégé ontology can be analysed on [85], which pretend to support an approach which can identify what kinds of manufacturing knowledge the different design decisions need. ManuHub: A Semantic Web System for Ontology-Based Service Management in Distributed Manufacturing Environments [11] is very dynamic framework, which takes all benefits of technology such as services, semantic, mapping and apply them on the manufacturing environment. The project OntoMaDa [70] aims to facilitate the exchange of experimental data, because it does not exist a standard data model for manufacturing processes for this kind of purpose. Nowadays the goal is to create more automatic ontologies, created and manipulated on-fly by the systems. Unfortunately, it needs the human hand, called semi-automatic, [62] it describes the mapping and the similarity computation to make this more interoperable.

Other ontologies addressing more specific domains in the manufacturing field were proposed, such as the design of ontologies for flexible manufacturing systems [82], for transport systems [57], for assembly lines control [12], for agent-based reconfiguration of production processes [1], for rent-a-car businesses [3] and for supply chain and logistic planning [2]. FRISCO is a manufacturing ontology reference that supports the organization of knowledge in automotive supply chains [35].

The problem here is to find the ontology that perfectly fits on the pre-requisites established for the GRACE production line domain, since some described ontologies are generic and others focus particular and specific application domains. The idea is to take the insights of several manufacturing ontologies, and particularly from PABADIS'PROMISE and ADACOR, and design a new ontology for the agent-based system integrating process and quality control in production lines, that will be generic enough within the boundaries of the problem specifics.

As an example, ADACOR ontology already defines several entities that can be used in the GRACE ontology. Since these entities are defined by their role on the multi-agent system it is very easy to complement with ontological concepts, very similar to PABADIS'PROMISE and ADACOR, for covering the GRACE particular domain.

Chapter 3

Description of the application domain

In this work, the ontology conceptualization is based on the manufacturing field and particularly production lines producing washing machines, which is the case study of the GRACE project. Due to confidentiality reasons, the description of the production line is not described in detail.

A Production line is a set of sequential work stations established along a line, aiming to realize operations (processing, assembly, quality control, etc.) to make a finished product, as illustrates the Figure 3.1.

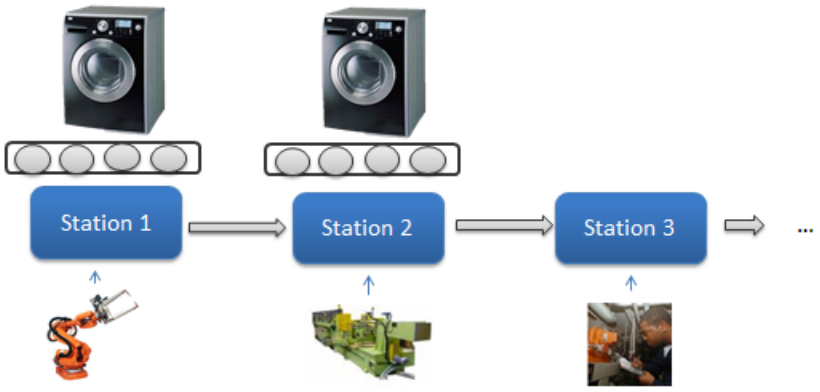

Figure 3.1: *Production line case study.*

The production line case study is actually composed by two parallel lines, which inter-

section in the middle. Thus, a machine, may or may not end up on a different line of where it started.

There are several types of resources identified in the line, each one having a different purpose. These resources are automated processes, or physical resources, such as product components or manufacturing stations, complementing among themselves to create a final product. For instance, some of the processes and physical resources are [60]:

- Prefabrication of sub-systems (drum, tub, cabinet).
- Assembly of the WM sub-systems (drum, tub, washing unit, cabinet, front panel, electronic board, etc.).
- Function to execute (assembly, screwing, etc.).

The screwing station, illustrated in Figure 3.2 is an example of a station disposed along the production line.

Figure 3.2: *Counter weight screwing station [60].*

Each station performs the operation only at one machine at a time. Thereby there is a relation one-to-one in terms of product versus station. There is a pre-defined sequence of

operations defining the process plan, which depends on the washing machine model. The production line has different implementation procedures, because there are different washing machines types of models.

Each pallet transporting the product being produced, is equipped with a programmable memory named moby, and has a unique identifier. Whenever a pallet arrives to a station, it is identified through a moby reader. Along the production line the moby installed in the pallet is collecting some relevant information from processes that are being executed, until it reaches the final testing area.

Along the production line, there are some special stations: quality control stations and repair stations, which are located through the line. These stations have mechanisms to test different components, different measurements of the washing machine components, vibration measurements, among others. If it is ensured that the quality control stations detect any irregularity in the implementation of the previous processes, the operator, on the repair stations, is able to take the appliance out of the production line and work on it in order to repair it. This happens because those anomalies are reported during its production process.

So this line is a great challenge for this project implementation since it is:

- robust, because it has a fairly number of output machines;
- flexible because a machine can be performed by different stations accordingly to different lines.

Chapter 4

Implementation of the GRACE Multi-agent System Solution

This chapter briefly describes the specification and implementation of the multi-agent systems infrastructure for the described case study.

4.1 Specification of the Multi-agent System

The GRACE MAS architecture was inspired in some MAS architectures [10], [47] but taking into consideration some particularities of the case study. The development process followed main steps:

- The identification of the types of agents and their roles and functions.
- The specification of individual behaviours (by using a formal language, namely the Petri nets formalism that is suitable to model dynamic, concurrent behaviours).
- The specification of the interaction patterns and cooperation/coordination mechanisms (by using Unified Modelling Language (UML) sequence diagrams and communication diagrams) for modelling the overall behaviour of the multi-agent system that emerges from the interactions among its individuals.
- Implementation using an agent development framework.

The GRACE MAS considers the distribution of the manufacturing functions by several agents, each one having a specific process to control [49]:

- **Product Type Agents (PTA),** represent the catalogue of products/parts that can be produced by the production line and contains the process and product knowledge required to produce the product, namely the product structure and the process plan. The PTA agents, as well the IMA agents, don't act at the operational execution level but instead in an higher level of control without hard real-time constraints.

- **Product Agents (PA),** manage the production of product instances in the plant/production line (e.g., washing machines and drums). They hold a process plan to produce the product and interact with the RA agents for the process and quality control.

- **Resource Agents (RA)**, are related to the physical resources of the production line, such as robots, quality control stations and operators. They manage the execution of their production/testing/transportation/assembly operations in the production line.

- **Independent Meta Agents (IMA)**, introduce a kind of hierarchy in the decentralized system, allowing the implementation of global supervisory control and optimized planning and decision-making mechanisms, e.g. defining and adapting global policies for the system. In opposite to the PA and RA agents, that are placed at the operational execution level and are mandatory, the IMA agents are positioned in a higher strategic level and are not mandatory (i.e. the system can continue working without them, however losing some optimization).

Due to the difficult to represent the behaviour of the intelligent and distributed multi-agent systems, a formal specification is crucial to guarantee that the model represents correctly the specifications of the real system. Just like happens in ontologies, it is necessary, before of the MAS implementation, the specification of the behaviours, and their validation are mandatory to avoid mistakes in the future implementation.

The importance of the right tool to specify the MAS behaviour is one variable to take into account when it is necessary to accomplish the previous formalisms. The modelling of the agents' behaviours with UML (Unified Modelling Language) activity diagrams [71],

which is a modelling tool that is adequate to model object-oriented systems, is the most obvious choice, but is not the best tool for the project needs, since it misses the formal validation of the model. The Petri nets formalism [69] is a formal modelling tool, based on mathematical formalisms. With Petri nets it is possible to accomplish the modelling, simulation, and mathematical validation of the agent's life-cycles. Having this in mind, the Petri nets formalism was used to specify the MAS behaviour.

The core of this thesis is not to explain the GRACE agents' behaviours, and only one example is given. Further detail, including the modelling and validation of all MAS system is available on [48], [49], and a large description of the agents' can be seen on the document [59].

In this document, the specification of the agent behaviour is illustrated for the PTA. For this purpose. Figure 4.1 represents the PTA's behaviour. Using the Petri nets formalism.

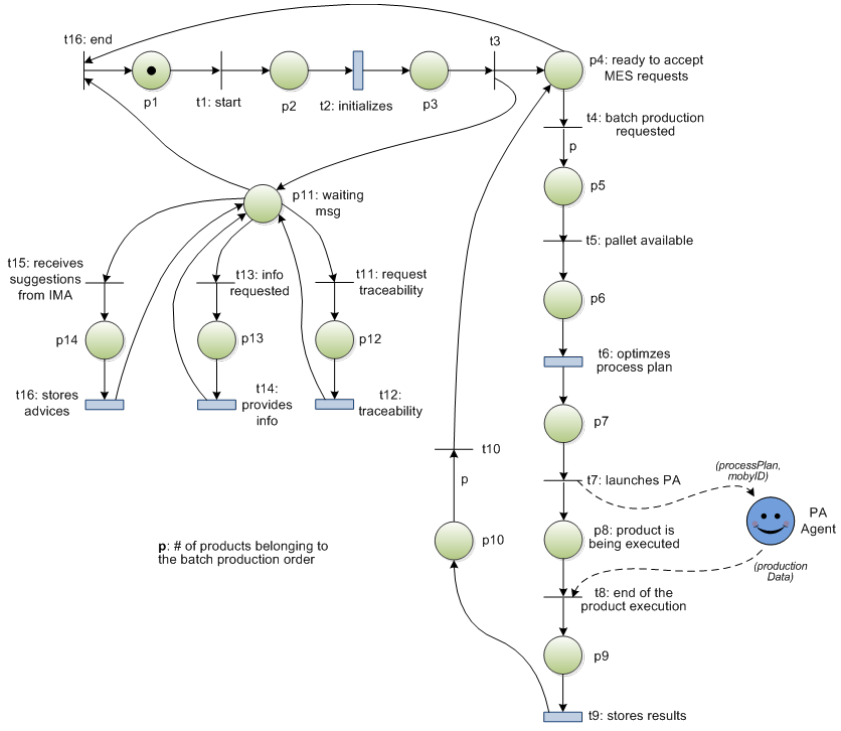

Figure 4.1: *The PTA agent behaviour model* [48].

Each Petri net model contains several timed transitions, which represents functions. As example, in Figure 4.1, the transition t_2 represents the functions related to the connection to the database, starting the agent's GUI, and registration of the agent's skills that are on the agent's profiles. In a similar manner, the transition t_6 represents the optimization of the process plan. These transitions represent complex functions that can be exploded by a more detailed sub-Petri nets model.

The PTA agent, after its initialization, enters in a state where it waits for a production order to be executed. This order involves the execution of p products. Once the request occurs, the PTA agent launches PA agents according to the availability of the pallets in the production line. In the transition t_7 the PTA agent interacts with other agents, namely the PA.

A multi-agent system emerges from the global interactions of the agents' behaviours. Each agent contributes for the system with its own behaviour. Figure 4.2 represents the global view of the agent's interactions.

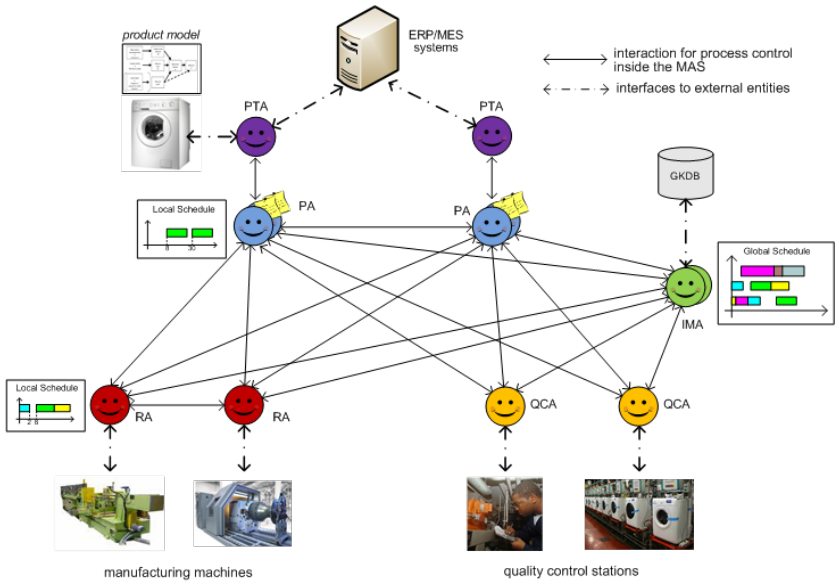

Figure 4.2: *Multi-agent system architecture for production lines [49].*

Concisely, the PTA agents receive instructions from the MES (Manufacturing Execution Systems) system and launch PA agents to perform the production requests, trading product

and process planning information. The PA agents cooperate with the RA agents during the execution of the process plan. PA and RA agents interact with the IMA to provide feedback information about the execution of the operations and the process plans and to receive optimized guidelines to improve their execution, allowing the attainment of a global modular, distributed, adaptive and reconfigurable control platform.

With the Petri nets formalism, the agents behaviour were formalized, but it is not possible to represent the interactions among different models. This means that it is necessary to model the interactions with a diagram of interactions.

Interaction patterns are required to model the agent's cooperation. This aims to coordinate their actions to produce a product, enhancing the integration and adaptation of the production and quality control processes. Figure 4.3 illustrates an example of this protocol, which follows the FIPA protocols prerequisites.

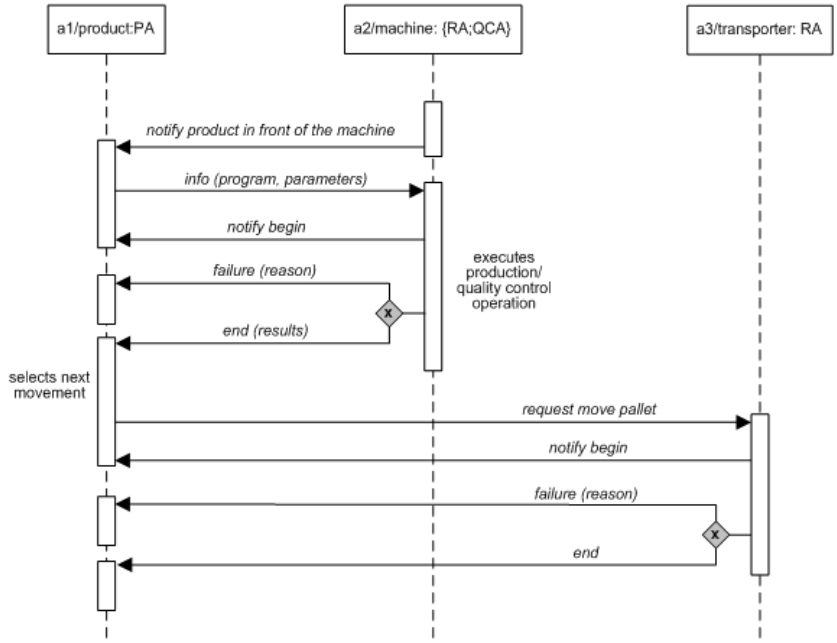

Figure 4.3: *Interaction diagram for the operation execution.*

Firstly, the RA agent detects that a pallet has arrived to its machine station, by reading the *moby* that is associated to the pallet, and notifies the PA agent. The PA determines the program and the parameters for RA to execute, and send it back to RA. Once the RA agent

finishes the program execution, it sends another message to PA to inform the result of it, which could be successful or failure. Reaching to this point, the PA agent check the process plan for further operations and request a movement of the pallet to the next station to a transport resource agent, which will deliver the pallet in the target station. All the GRACE multi-agent system interactions are formalized in this mode.

4.2 Implementation of the Multi-agent System

There are several frameworks available for the implementation of agents based solutions. These frameworks share the facility of the developers to abstract technical details and advance to the implementation of the agents' behaviours. The development of multi-agent system solutions requires the implementation of features not supported by usual programming languages, such as message transport, encoding and parsing, white and yellow pages services, ontologies for common understanding and agent life-cycle management services. This leads to an increase of productivity, reducing the implementation time for further detail see appendix B.2.

After studying several tools, see appendix B.1 with a comparison analysis of several frameworks, the JADE framework was selected. The main reasons for this are the fact of being FIPA Compliant and having a Freeware license, with source code available on JADE website.

JADE is a Java-based architecture that uses the Java Remote Method Invocation (RMI) to support the creation of distributed Java technology-based to Java applications. Each agent is implemented with Java "threads" and associated with a container.

Aiming to structure the implementation of the source code, a set of packages was created, as illustrated in Figure 4.4 separating the concepts and functions associated to the MAS application.

Each package contains a set of classes that executes the functionalities associated to the agents. Some packages are related to only one agent, for example the PA package that is only associated to the PA agent. As illustrated in Figure 4.5.

This PA package contains a set of classes, namely two for the agent (*PA* and *WaitingMessage* class) and one related to the GUI (*formPA* class).

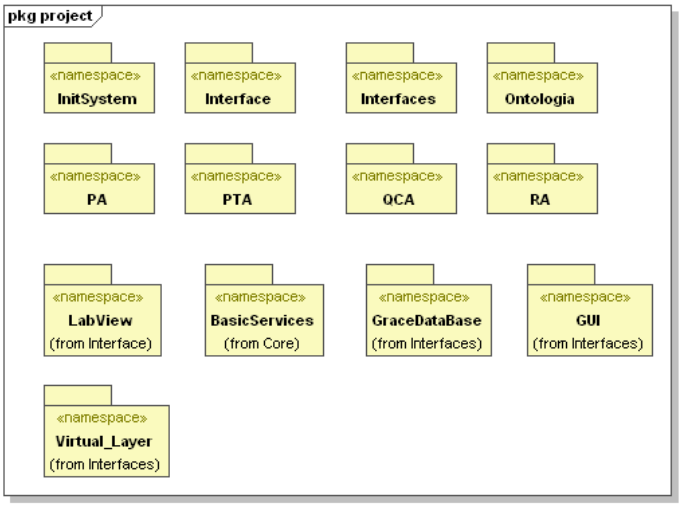

Figure 4.4: *GRACE project packages.*

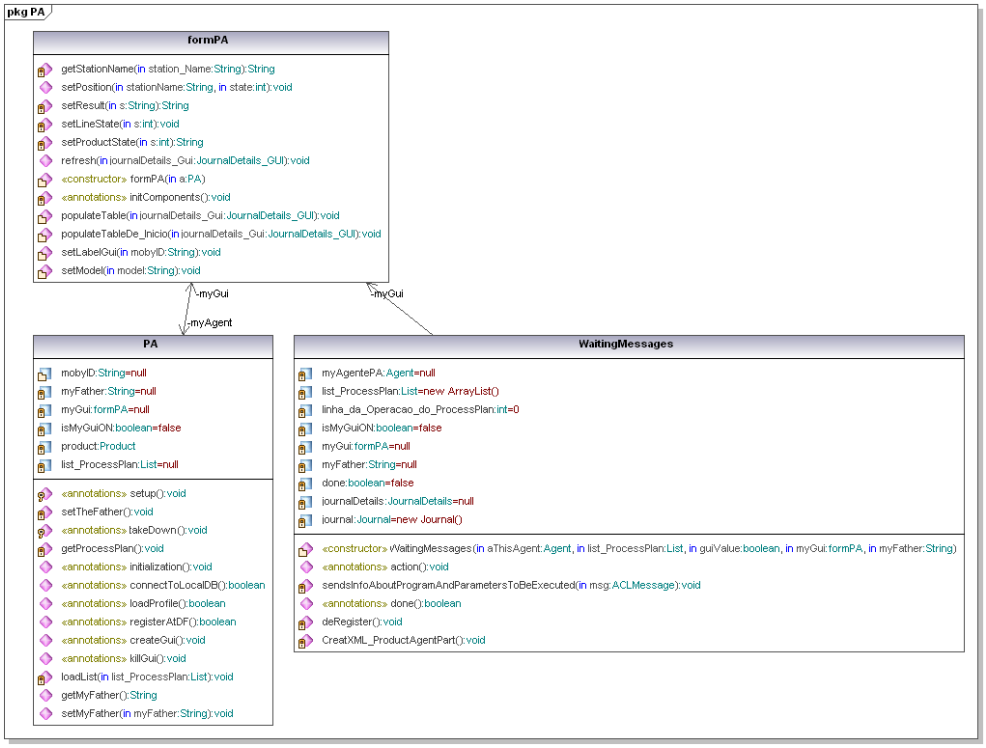

Figure 4.5: *Description of the PA package .*

Some packages provides common functions that was used by the agents, namely the package "BasicServices", as illustrated in Figure 4.6.

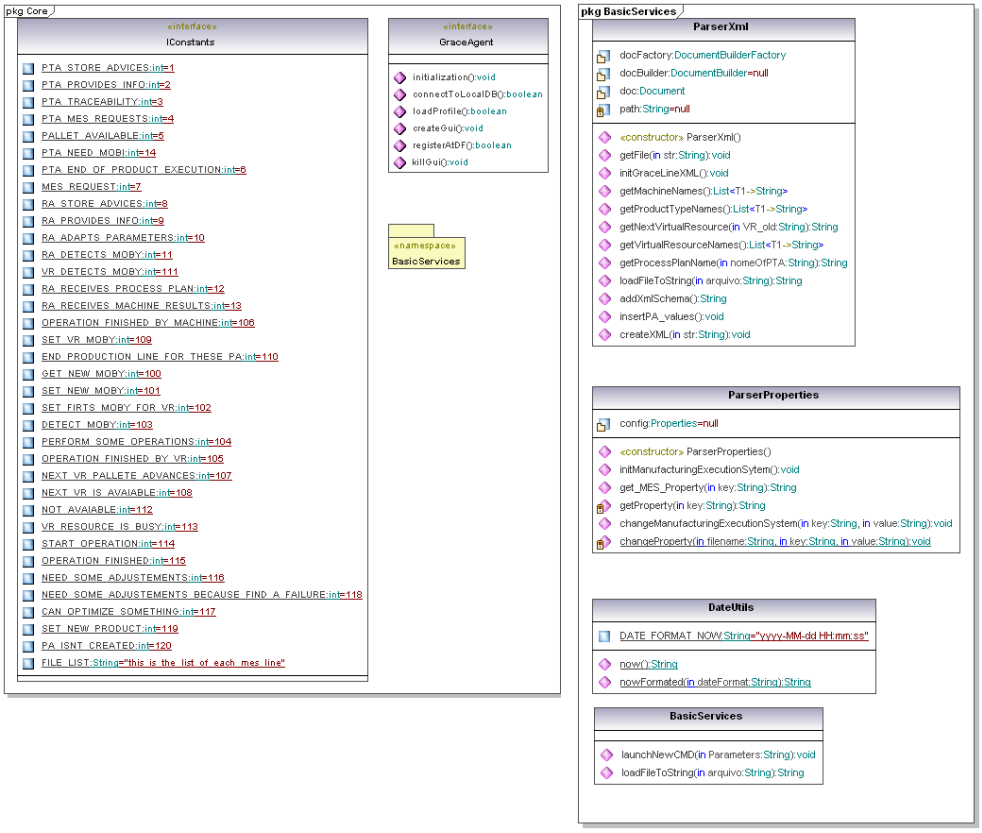

Figure 4.6: *Description of the package "Basic Services".*

A GRACE agent is a class that extends the JADE *Agent* class, inheriting basic functionalities. The starting point of the agent is the method *setup()*, which is the first to be executed. The following extract of code illustrates the structure of the RA agent.

```
package RA;
public class RA extends Agent implements GraceAgent{
  private formRA_ myGui = null;
  private boolean isMyGuiON = false;
  @Override
```

```
  protected void setup(){
    initialization();
    // alocate the behaviour to handle the receive the messages
    WaitingMessages waitingMessages = new WaitingMessages(this, isMyGuiON, myGui);
    addBehaviour(waitingMessages);
  }
  ...
}/* end of RA Class
```

The agent inherits basic functionalities, such as registration services, remote management and send/receive ACL messages [7]. These functionalities were extended with features that represent the specific behaviour of the agent, as described in [58]. Analysing the previous piece of code it is possible to verify that in the beginning of the setup method, a initialization function is executed being responsible to register the agents skills in the DF, connect to the local database, and create a GUI component as illustrated in the following piece of code.

```
@Override
public void initialization(){
  loadProfile();
  registerAtDF();
  connectToLocalDB();
  createGui();
}
@Override
public boolean registerAtDF(){
  boolean res = false;
  DFAgentDescription dfd = new DFAgentDescription();
  dfd.setName(getAID());
  ServiceDescription service = new ServiceDescription();
  service.setType("servico_RA");
  service.setName(getLocalName());
  dfd.addServices(service);
  try {
    DFService.register(this, dfd);
    ...
  } ...
}
```

The communication between distributed agents is done over the Ethernet network, using TCP/IP protocol and is asynchronous, i.e. an agent that sends a message continues its execution without the need to wait for the response. The messages specified in the GRACE multi-agent system are encoded using the FIPA-ACL communication language to achieve normalized communication between the agents, being the content of the messages formatted according to the FIPA-SL0 language. The meaning of the message content is standardized according to the GRACE ontology.

For this purpose and since the behaviour of the agent is driven by the messages received from the other agents (i.e. incoming events), a cyclic behaviour called *WaitingMessages* is launched in the *setup()* method. This behaviour is a Java class that is waiting for the arrival of messages, using the block() method to block the behaviour until a message arrives and the receive() method to extract the incoming message, as illustrated in the next extract of code.

```
class WaitingMessages extends CyclicBehaviour implements IConstants, IConstants_GUI {
  //atributes/*...*/
  WaitingMessages(RA aThis, boolean myGuiON, formRA_ myGui){
  myAgenteRA = aThis;
  this.myGui = myGui;
  this.isMyGuiON = myGuiON;
}
@Override
public void action(){
  ACLMessage msg = myAgent.receive();
  if (msg != null) {
    Integer key = Integer.parseInt(msg.getConversationId());
      switch (key) {
        case RA_STORE_ADVICES:
            myAgent.addBehaviour(new StoreAdvices()); //FuncRA_t13
            break;
        case RA_PROVIDES_INFO:
            myAgent.addBehaviour(new ProvidesInfo());  //FunRA_t7
            break;
        case RA_ADAPTS_PARAMETERS:
            adaptsParameters();  //Function RA_ t5
            break;
```

```
            case VR_DETECTS_MOBY:
                System.out.println("[RA] RA recebeu o tick do VR");
           }
      }
      else {
         block();
      }
   } // end of WaitingMessages class
```

The arrival of a message triggers a set of actions related to decode the message and select the proper actions to be performed. Looking to the code, if the message is not null, it is verified the conversation ID of the message, and depending of the conversation ID of the message a different behaviour or function is called. As an example, if the received message has a RA_PROVIDES_INFO identification, a new behaviour called *ProvidesInfo()* is triggered. Note that after triggering the action related to the received message, the *WaitingMessage*s behaviour continues waiting for incoming messages continuously. All agents in the GRACE system are able to receive messages following this approach. The behaviours launched in the setup() method and those posteriorly invoked within these behaviours are also provided by the resource agent package in the form of Java classes.

Besides all of these internal behaviours, a GRACE agent has connections with legacy systems, e.g. with production database or quality control stations.

As example, the QCA may interact with LabView applications stored in the quality control stations. The LabView application intends to perform quality control tests, but that information should return to the agent.

For this purpose an interface linking the QCA and the LabView application was developed using a sockets communication [52], which classes are aggregated in the LabView package illustrated in Figure 4.7.

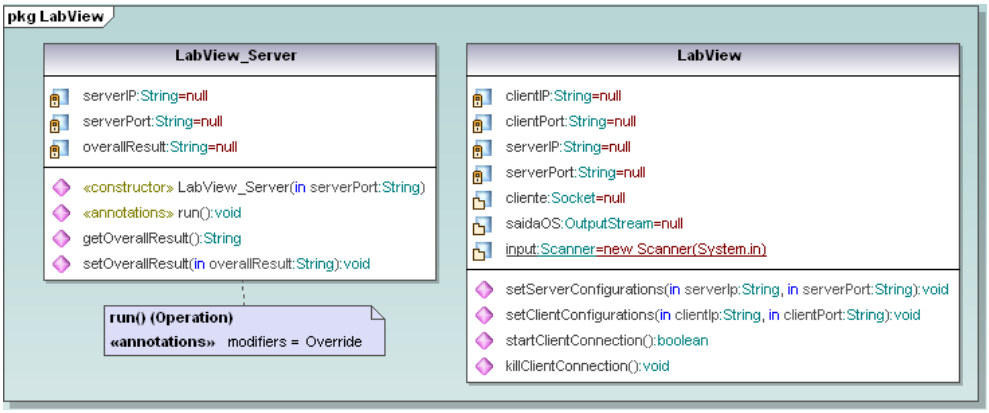

Figure 4.7: *Classes used on GRACE to handle the interfaces with LabView applications.*

The following piece of code illustrates the function need to perform correctly the notification of the Operation parameters to be executed.

```
if (owner.equals("Visual_Inspection"))
{
  try {
    LabView_Server server = new LabView_Server("5555");
    // LV Server
    LabView client = new LabView();
    client.setClientConfigurations("192.168.0.103", "5551");
    client.startClientConnection();
    client.killClientConnection();
    server.join();
    String result = server.getOverallResult();
  }
```

The *LabView* represents a class that is extended form the class Thread of Java. It is created one instance "*server*" to simulate a server socket from the binomial server - client. The client socket is created on the Labview application. Thus the inverse communication is developed, a client socket is created on agent side represented by the instance "*client*", and respectively configuration. With this sockets configuration it is possible to create a interface with Labview and JADE agents.

All the GRACE agents provide Graphical User Interfaces (GUIs). The GUIs are a way to provide the interface with the users to support the administration, management and monitoring of the system. Each type of agent provides different GUIs, since each type handles a particular set of information, and allows different types of interactions with users. In spite of providing different information, the GUIs of the several agents follow a common template of menus customized according to the agent's particularities. The use of a Java based framework, like JADE, to develop the system, offers the possibility of using Swing, a well-established toolkit to implement GUIs for desktop applications. Each type of agent in the GRACE system has its GUI implemented as an extension of the javax.swing.JFrame component. To perform the adequate interaction between both elements, the agent has a reference to the GUI form and this one have a reference to its owner agent.

The data shown by the GUI is stored in the local database, and the graphical interface is refresh when a event occurs, e.g. the reception of messages indicating changed conditions.

Although following the same structure, the GUI for each agent is different and customized according to its particularities.

In the IMA agent, the GUI illustrated in Figure 4.8, is useful to provide a global perspective of the entire production system (or part of it if considering different IMAs). The GUI for the IMA agent presents a global view of the system taking advantage of the data collection performed over the time for global adaptation/optimization and stored in the IMA's SQL database.

This GUI will be the best candidate to be exported to a remote interface if necessary, because it is the only one that has the global view of the line.

The other GUIs are not so crucial in the system but can be used to provide info to the system uses. The GUI for the PA, RA, PTA agents are illustrated in Figure.

The GUI for the PTA agent, presented in Figure 4.9, allows the visualization of the production orders (managed by PA agents) launched for the execution at the production line, and its current status. For those that already have finished its execution, it is possible to consult the following information: identification, start date and end date, the result of the execution and the current state.

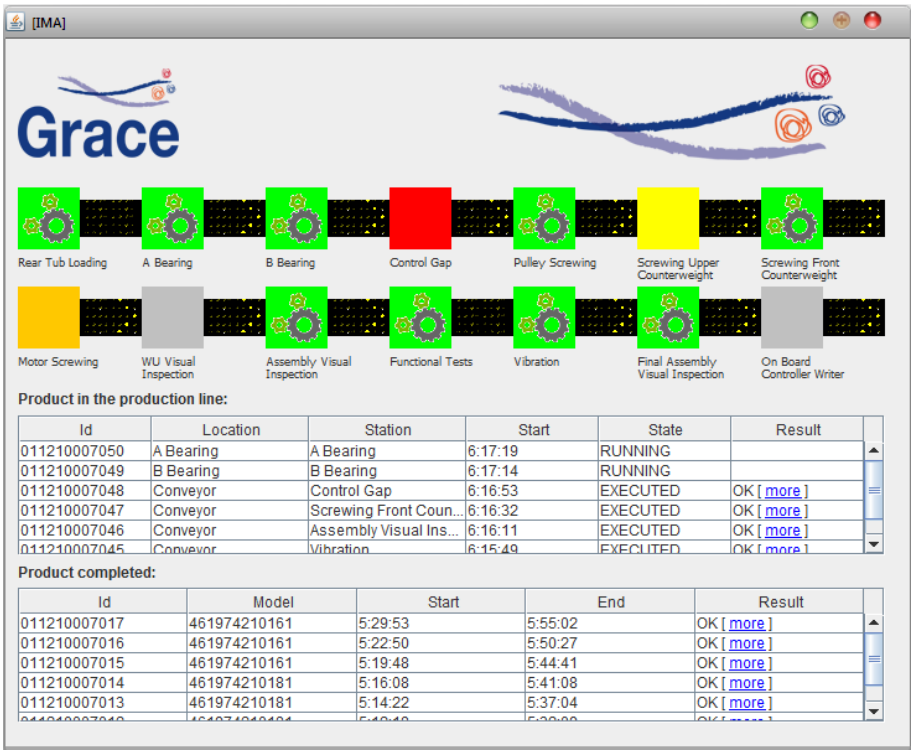

Figure 4.8: *Screenshot of the IMA's GUI.*

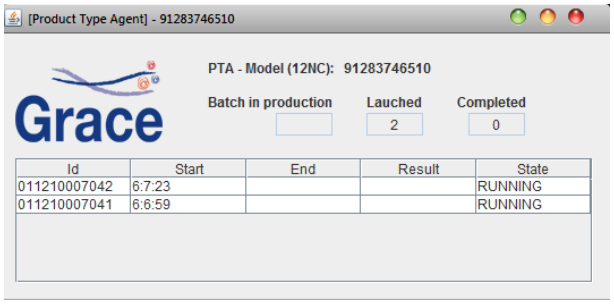

Figure 4.9: *Screenshot of the Product Type Agent.*

The GUI for the PA agent, shown in Figure 4.10, offers the information regarding the moby identifier and the product model, and permits the on-line monitoring of the production of the product instance in a graphical manner.

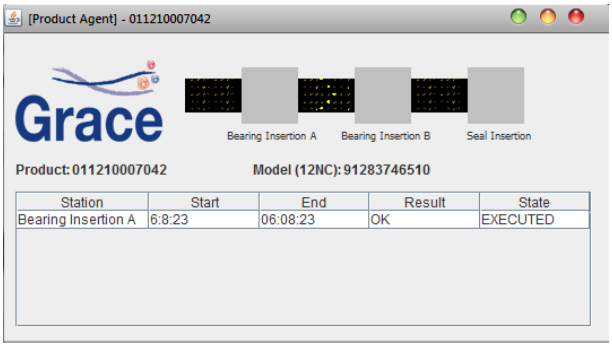

Figure 4.10: *Screenshot of the Product Agent.*

For each operation belonging to the process plan, is possible to visualize its current status state, the identification of the resource responsible for its execution, the start and end date, and the results from its execution. For immediate identification of the position of the product in the production line, a dynamic graphical representation of a segment of three resources is presented on top of the GUI. In this way it is possible to see the current location of the product and where it goes.

The GUI for the RA agents, shown in Figure 4.11, enables the visualization of the current state of the resource (e.g. running, free).

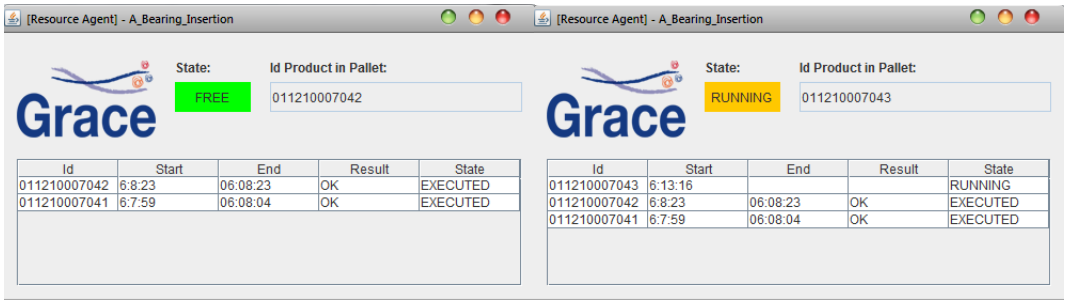

Figure 4.11: *Screenshot of the Resource Agent.*

The received notifications send by IMA agent as result of its trend analysis mechanism,

are reflected in the RA's GUI by the presentation of a warning message and the exhibition of the colour of the exhibited card (i.e. yellow, orange or red card) in the line that contains the product data (see Figure 4.12) [4].

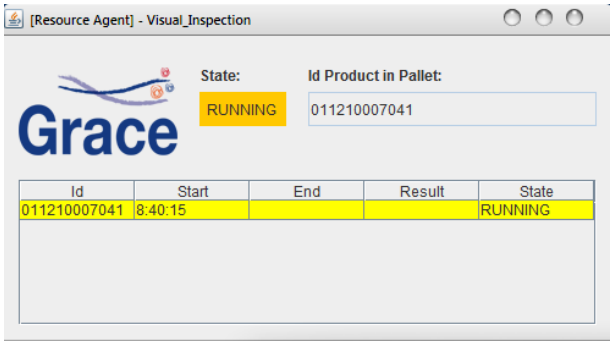

Figure 4.12: *Screenshot of the Resource Agent executing an Operation after Applying Adaptation Proced.*

At this stage, the MAS infrastructure is implemented and ready to accommodate the ontologies that will support the knowledge representation, e.g. to allow a correct exchange of messages among the agents.

Chapter 5

Design of the GRACE Ontology Schema

The implemented Multi-agent System, described in the previous chapter, is not completed if a proper ontology is not used. This chapter describes the ontology design.

5.1 Introduction

The proposed GRACE ontology aims to represent the knowledge associated to the washing machines production lines domain, which will be used in a multi-agent system application to integrate the production and quality control processes. This ontology considers some insights from PABADIS'PROMISE and ADACOR approaches as already mention before.

The ontology is founded on the definition of a taxonomy of manufacturing components, which contributes to the formalisation and understanding of the problem. The ontology schema defines the vocabulary terms used by distributed entities, the agents, and indicates the concepts (objects or classes), the predicates (relation between the classes), the terms (attributes of each class), and the meaning of each term (type of each attribute).

The design of an ontology passes by several steps, conceptualization, specification, instantiation, integration, evaluation and finally documentation. Making a very brief explanation and resuming only to three main phases, starting from the conceptualization of the ontology where the specific domain is defined, and one starts to think in more general concepts and specializing each one. Passing by the specification of the ontology schema, this is based on

the reunion of all these concepts, predicates and terms and then implemented on specific ontological software, followed by the instantiation of the schema. For an easy understanding, the GRACE ontology schema has been initially built using the UML class diagram format, and posteriorly edited and instantiated in the Protégé framework using the OWL language.

For every ontology reuse or created from zero, it is mandatory that it has a purpose, at least to have logic. It is important to be clear about the needs of the ontology.

The GRACE ontology aims to turn more interoperable the knowledge used by the multi-agent system. As already mention the agents only have a partial view of the system.

For this purpose, GRACE ontology will provide the data structure to organize the knowledge that is shared and exchanged between the agents and enable the interoperability between them. In particular, the GRACE ontology formalizes the structure of the knowledge related to:

- The resources available in the production line.
- Equipments available in the production line.
- The product and process models that describe how to produce the catalogue of products in the production line.
- The description of the production history executed in the production line, including the results from the inspection tests.

The GRACE ontology intends to formalize each concept, each process, and each object in order to have all entities recognized, which lead to a better conceptualization and obviously a good implementation, increasing quality control processes. During this process, the difficulty was referent to how and whether it be used the ontologies that already exist. Taking in consideration that GRACE ontology is based on ADACOR and PABADIS'PROMISE, it appears that question of. The solution was picking the best of these approaches and components with new ones addressing the particularities of the domain. The global view of the GRACE ontology can be seen in Figure 5.1.

In the Figure, it is represented all classes, relations, and attributes. The following sections will detail more deeply each term.

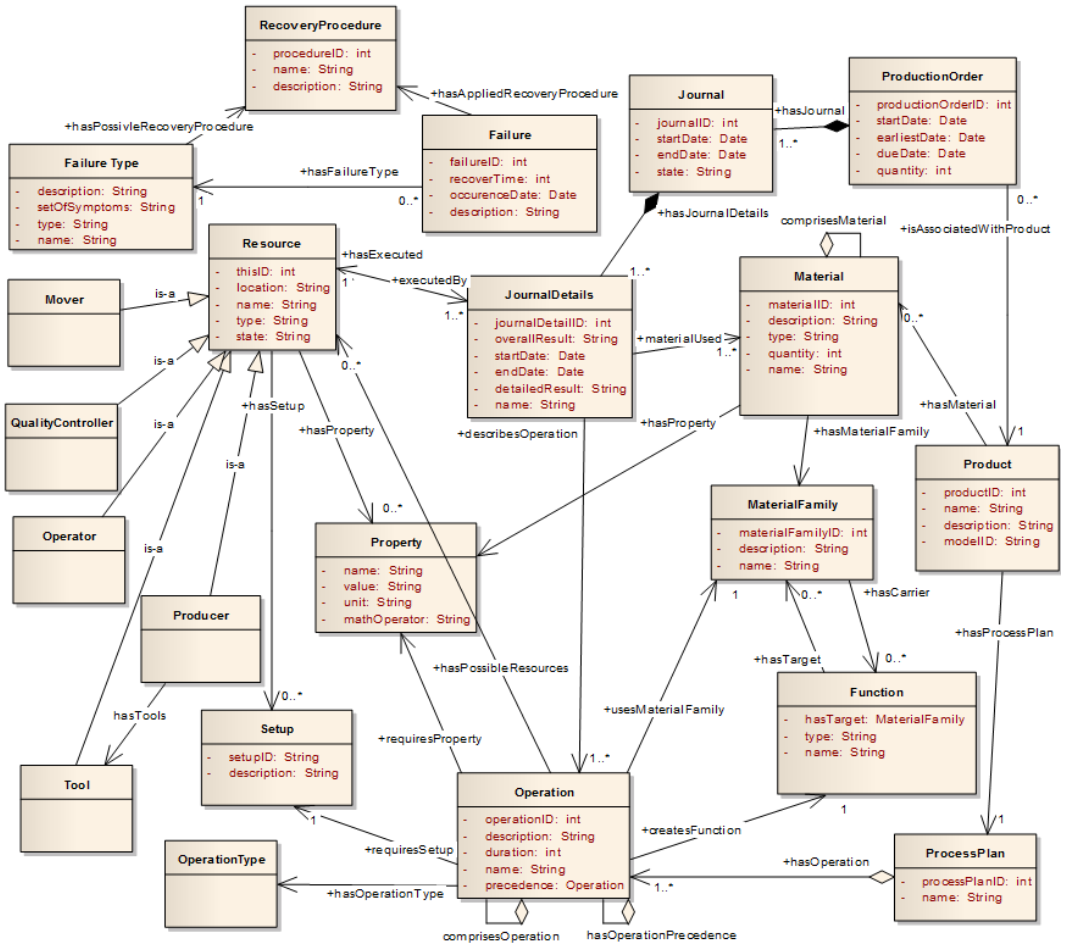

Figure 5.1: *GRACE Ontology Schema.*

5.2 Concepts

Concepts are expressions that indicate domain entities with a complex structure that can be defined in terms of classes or objects. Figure 5.2 illustrates the concepts of the GRACE ontology, as represented in the Protégé editor.

The main concepts defined in the GRACE ontology are described as follows:

- Failure: description of an occurred perturbation, including the occurrence date, the applied recover procedure and the recovery time.

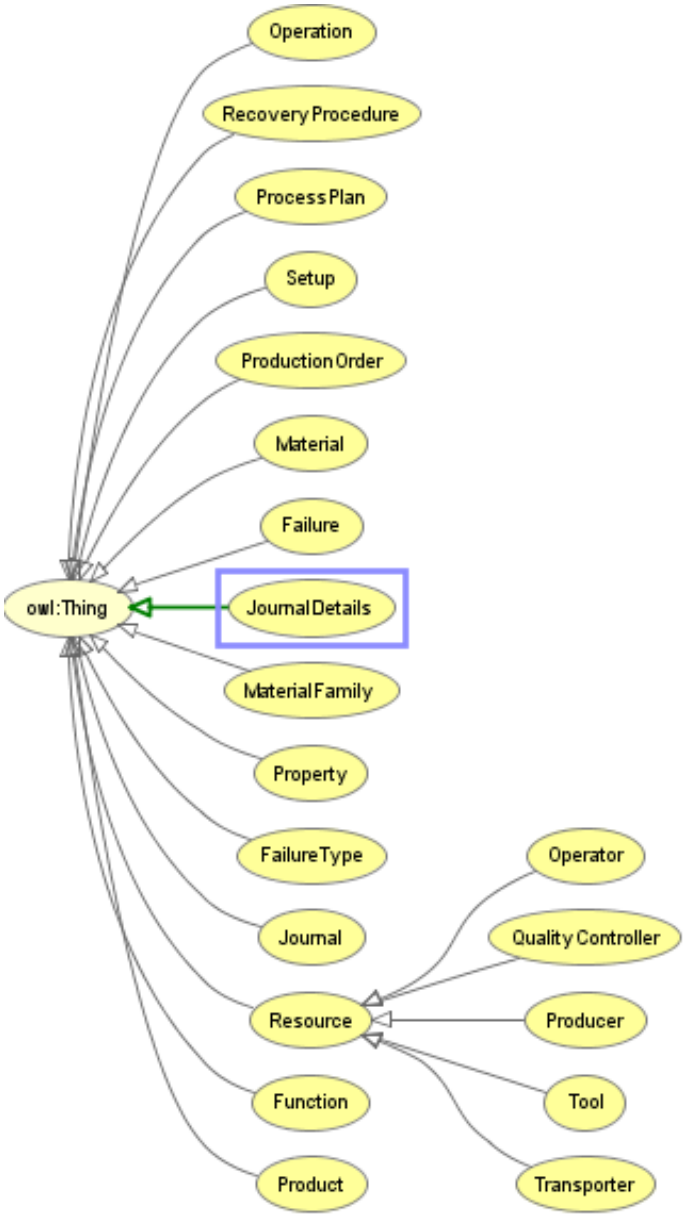

Figure 5.2: *Concepts of the GRACE ontology .*

- FailureType: unexpected event type, like machine failure or delay, which degrades the execution of a production plan.
- Function: entity that describes interactions among product components (materials)

and/or external environment, e.g. tub contains water and drum move clothes; it is a product function.

- Journal: description of the production of a product instance belonging to a production order executed in the production line, including the list of operations performed and the resources that have executed each operation.
- JournalDetails: entity that describes the execution of an operation, including the processing time, participants (e.g. type and number of resources), dates and achieved results.
- Material: entity used during the production process, e.g. tubs, blocks of steel, bearings, nuts and bolts, according to the BOM (Bill of Material).
- MaterialFamily: family of the material used during the production process, e.g. bearing or tub (note that each material family could have different materials, e.g. for the family bearing, it is possible to have the bearing A and B).
- Operation: a job executed by one resource, like drilling, welding, assembly, inspection and maintenance that may add value to the product or may measure the value of the product, e.g. the quality control.
- Operator: a specialized human resource entity that is responsible for the execution of manual operations, such as an operator connecting the electrical cables.
- ProcessPlan: represents the manufacturing process to produce a product, i.e. the description of a sequence of operations (for producing a product) with temporal constraints like precedence of execution.
- Producer: a specialized resource entity that is responsible for the execution of producing operations, such as a welding robot or a CNC (Computer Numerical Control) machine.
- Product: economic entity (finished or semi-finished), which is produced by the enterprise in a value-adding process (it includes a Bill of Materials (BOM), i.e. the list of materials that are considered as components of a final or intermediate product; it also includes the quantity required of each material).

- ProductionOrder: entity obtained by aggregating customer and forecast orders for the production of products, and provided by the ERP (Enterprise Resource Planning)/MES (Manufacturing Execution System) system.
- Property: an attribute that characterizes a resource (i.e. a skill) or that a resource should satisfy to execute an operation (i.e. a requirement). It includes a mathematical operator associated to the property value, e.g. a speed equal to 2000 r.p.m..
- QualityController: a specialized resource entity that is responsible for the execution of measurement and diagnosis operations, such as a vision control station or a vibration control station.
- RecoveryProcedure: entity that describes the procedure to recover from the occurrence of a failure.
- Resource: entity that can execute a certain range of operations as long as its capacity is not exceeded. Producer, quality controller, transporter, operator and tool are specializations of resource and inherit its characteristics.
- Setup: set of actions that it is necessary to execute in order to prepare a manufacturing resource for the execution of a range of operations.
- Tool: a specialized resource entity representing the physical devices used by producer stations and by operators to execute their processing operations, e.g. screw driver for screwing the counterweights; it may include the physical devices used by transporter resources to execute their handling operations, e.g. grippers.
- Transporter: a specialized resource entity that is responsible for the execution of handling/transporting operations, such as an Auto-guided Vehicle (AGV) or a conveyor.

5.3 Predicates

Relations or predicates establish the relationships among the concepts, being characterized by the type of relation and its cardinality.

The most common types of relations are the association (representing a relationship between two objects defining its multiplicity), aggregation (a specialization of the association relationship, but only in one directional way), generalization (representing an inheritance of objects in a form of a "is-a" relationship) and composition (a special case of aggregation when the container object has a strong relation with another object; the second cannot exist without the other one). For example, Figure 5.3 illustrates the Product and Process Plan concepts that are connected through the relations hasProcessPlan, hasProduct and hasProductPrecedence, all of them are associations.

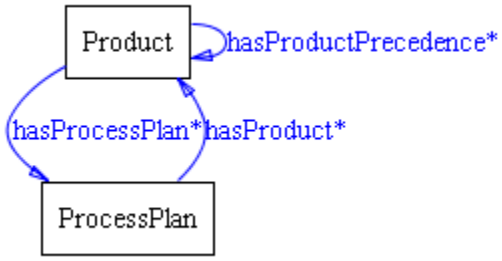

Figure 5.3: *The relation between the Product and ProcessPlan concepts .*

Associated to the relation appears the concept of cardinality, which indicates the number of object instances in the association (in case of multiple instances the relation is marked with the symbol "*"). For the example illustrated in Figure 5.3, the relation hasProduct has cardinality 1, which means that a product only have one process plan; on the other hand, the relation hasProductPrecedence has cardinality 0..*, which means that a product has several precedences from other products.

Note that the relation hasProcessPlan has an inverse relation that is hasProduct illustrated on Figure 5.4. This could be useful to represent different paths of knowledge and consequently increase the ontology knowledge.

The predicate *describesOperation* establishes the relation between the class "*JournalDetails*" and the class "*Operation*", meaning that the details about the execution of the operation are reported in the journal details, being formally defined as follows:

- *describesOperation* (x, y)journal details x describes the execution of the operation y.

- Domain: $\forall x \exists y(R(x,y) \rightarrow C(x))$, where x is the JournalDetails.
- Range:$\forall x, y(R(x,y) \rightarrow C(y))$, where$y$ is the Operation.

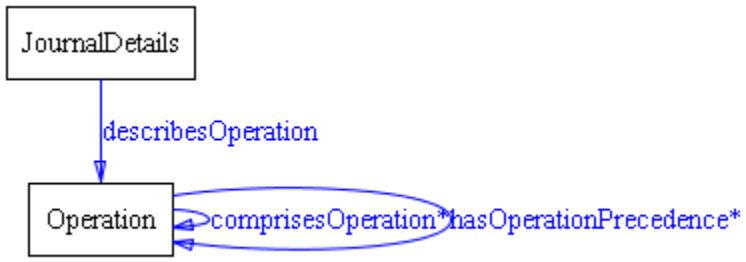

Figure 5.4: *The relation between the JournalDetails and Operation concepts .*

The predicate *executedBy* establishes the relation between the class "*JournalDetails*" and the class "*Resource*", describing the resource that was executed the operation described in the journal details, being formally defined as follows:

- *executedBy*$(x,y)$the operation described in the journal details x was executed by the resource$y$.
- Domain: $\forall x \exists y(R(x,y) \rightarrow C(x))$, where x is the JournalDetails.
- Range:$\forall x, y(R(x,y) \rightarrow C(y))$, where$y$ is the Resource.

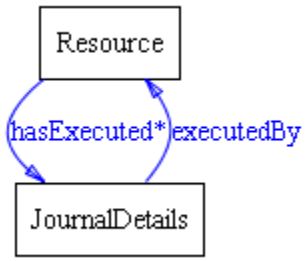

Figure 5.5: *The relations between the Resource and JournalDetails concepts .*

At this stage, the relations defined in the GRACE schema ontology are identified and described. Later on, in the section related to the restrictions, the description of the relations will be completed by the definition of the type of relation (connection) and the cardinality associated.

Due to the fact that the design of the ontology and its respective description are quite extensive, the rest of the relations are described on the appendix A.1. Also a a design of the predicates is represented on the appendix A.1.1.

5.4 Attributes

Attributes are values relative to properties of concepts. These values could be DataTypes (e.g. string, integer) or PropertyTypes (i.e. ontology concepts, e.g. resource and operation, established as relations). These attributes work like restrictions to the concepts (other types of restrictions will be analysed in the next section).

The following Table 5.1 defines the main attributes established in the GRACE ontology. In this definition, the item Domain refers to the concept that holds the attribute and the item Range refers to the type of that attribute, e.g. "XSD.Integer" in case of Integer or "XSD.string" in case of String.

From the analysis of the list of attributes, the concept Property requires a special attention. The tuple {name, value, unit, mathOperator}, associated to the datatype property, represents the properties and characteristics exhibited by a resource or required by an operation to be performed. Examples of properties are:

- **LifeTime**: a positive rational number that defines the life time of a tool (expressed in seconds).
- **Axes**: a non-negative integer, e.g. the number of axes of a machine.
- **ProcessingType**: a type of processing e.g. turning, milling, or drilling.
- **Repeatability**: a non-negative float, it gives an indication about the degree to which repeated measurements under unchanged conditions show the same results (expressed in mm).

Table 5.1: *Example of GRACE ontology attributes.*

Attribute	Description	Domain	Range
description	A statement describing something, e.g. a product or a setup	Setup, Product, FailureType, Material, MaterialFamily, Operation and RecoveryProcedure	XSD.string
detailedResult	The detailed description of the results obtained in a measurement/testing operation	JournalDetails	XSD.string
dueDate	The date on which an obligation, e.g. the production of a product, must be accomplished	ProdutctionOrder	XSD.date
earliestDate	The date before which an activity or event cannot start.	ProdutctionOrder	XSD.date
endTime	The date describing the end of the execution of an activity	Journal, Journal Details	XSD.date
failureID	A non-negative integer number that provides the unique identification of the failure	Failure	XSD.int
functionType	The type of the failure that can occur during the production execution	Function	XSD.string

- **FeedRate**: a positive rational number, it gives the feed rate of a specific axis (expressed in mm/rot).
- **SpindleSpeed**: a range of non-negative integers, it gives the spindle speed in the form [min, max] (expressed in rpm).
- **Tailstock**: a range of non-negative integers, it gives the size in the form [min,max] of pieces that the machine can process (expressed in mm).
- **Payload**: positive integer, it gives the maximum load of the robot that guarantees the repeatability (expressed in kg).

- **MaxReachability**: positive integer, it gives the work volume of the robot (expressed in mm).
- **MagazineCapacity**: non-negative integer, it gives the number of tools or grippers that the magazine of a machine or robot can store.
- **CuttingSpeed**: a positive rational number, it gives the cutting speed (expressed in mm/s).
- **Wear**: a positive number defining the wear of a cutting tool (expressed in mm).
- **CycleTime**: a positive number defining the length of the performed quality control task (expressed in seconds).
- **PercentOfScraps**: a positive number defining the percentage of scraps identified (referred to the total number of inspected items).

Due to the fact that the design of the ontology and its respective description are quite extensive, the rest of the relations are on the appendix A.2.

5.5 Restrictions

The design of an ontology may consider the restrictions associated to the ontological concepts, restricting the values and the cardinality associated to the identified predicates. The restrictions related to the values are created to implement the obligation of having the relation among concepts, and the restrictions about the cardinality are related to create the obligation in terms of number in those relations. Here, it is also important to consider the restriction in the attributes associated to the allowed values.

This section defines the predicates restrictions, by directly mapping the UML classes into the OWL concepts restrictions [39] see appendix A.3 for more details. In this description, each concept is separately analysed and identified the restrictions of the existing predicates associated to the concept. The fulfilment of the identified restrictions is crucial to preserve the consistency of the ontology. It will be described only two examples of the restriction; the rest is in the appendix A.3, thus making it easier to read.

The class "*Operation*" has several attributes as illustrated in Figure 5.6. Some of them are relations with the classes, namely requiresProperty (with the class "*Property*"), requiresSetup (with the class "*Setup*"), createsFunction (with the class "*Function*"), hasPossibleResources (with the class "*Resource*"), usesMaterialFamily (with the class "*MaterialFamily*"), and comprisesOperation and hasOperationPrecedence (with themselves). Additionally, it has DataType properties, such as duration, *name*, *operationID* and *type*.

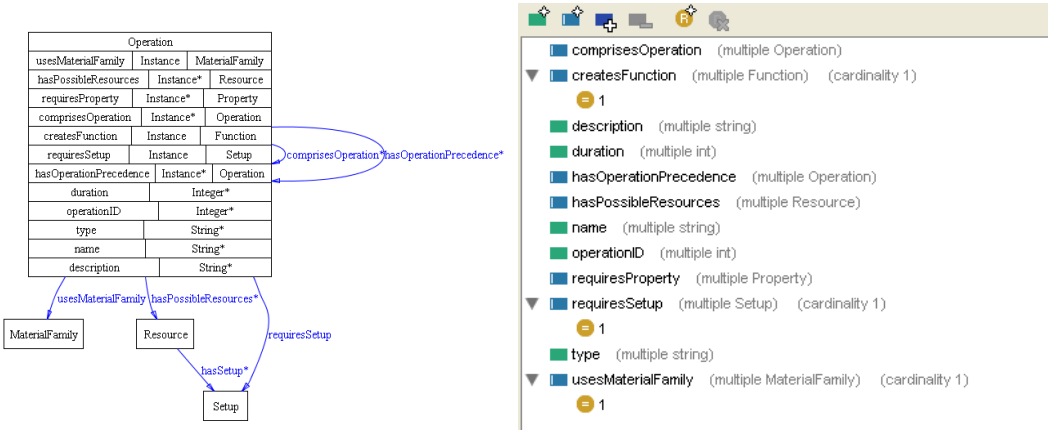

Figure 5.6: *Restrictions of predicates associated to the class "Operation".*

The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicates **createsFunction**, **requiresSetup** and **usesMaterialFamily** have the restriction minCardinality = 1, i.e. the cardinality of these relations is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow | \left\{ y | R\left(x, y\right) \right\} | = N \right) \text{ the N is 1.} \tag{5.5.1}$$

The predicates **requiresProperty**, **hasPossibleResources**, **comprisesOperation**, and **hasOperationPrecedence** don't present any restriction in terms of cardinality.

The class "Failure" has several attributes as illustrated in Figure 5.7. Some of them are relations with the classes, namely hasFailureType (with the class "FailureType") and hasAppliedRecoveryProcedure (with the class "RecoveryProcedure"). Additionally, it has DataType properties, such as failureID, occurrenceDate and recoveryTime.

The defined relations have specific restrictions. In terms of the type of connection, all of

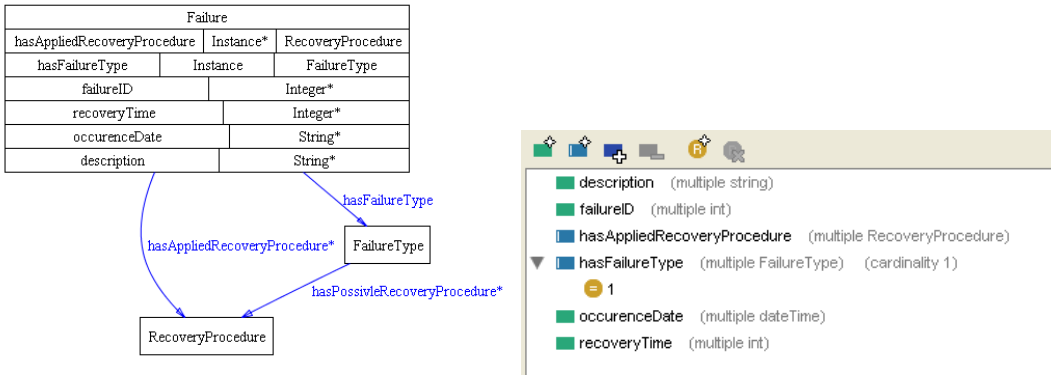

Figure 5.7: *Restrictions of predicates associated to the class "Failure" .*

them are associations among the classes. In terms of cardinality, the predicate hasFailureType has the restriction $minCardinality = 1$, i.e. the cardinality of this relation is equal to 1, or in a more formal manner

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.} \tag{5.5.2}$$

The predicate **hasAppliedRecoveryProcedure** don't present any restriction in terms of cardinality.

Due to the fact that the ontology is very restricted, a considerable number of restrictions have been created, it is important to represent them, but it is quite extensive, so for further consultation on the appendix A.3.

5.6 Validation and Evaluation

The evaluation for maintain a good practice should be created, and if possible with several approaches to evaluate. This means in terms of concepts and instantiation to cover the some possible paths, making a validation of its correctness and the adjustment of some ontological entities.

Several works exist in literature about ontology's evaluation [27], [31]. So this enforces the real needs for this work. To sum up, the most important features on the evaluation process of the ontology are the structure, content, syntax, and a set of semantic properties

that guarantee the coherence, completeness, consistency of the definitions.

At this phase, the ontology was designed and edited in the Protégé framework. For this purpose, this chapter describes the validation of the designed ontology by using the Protégé framework. The full validation is on the appendix A.4.

The validation can be performed by using JENA, which is a Java framework for building Semantic Web (JENA) [37] that provides the environment to handle the RDF, RDFS and OWL languages. It provides several reasoning tools, like Pellet (http://pellet.owldl.com), to check the consistency of the ontology and all the characteristics of an ontology. The validation test was performed by using the Pellet tool provided by the Protégé framework, which allows verifying the consistency of the ontology based on four checking tests: the subsumption checking, the equivalence checking, the consistency checking and the instantiation checking.

The GRACE ontology has passed with success the set of checking tests, illustrated on the Figure 5.8.

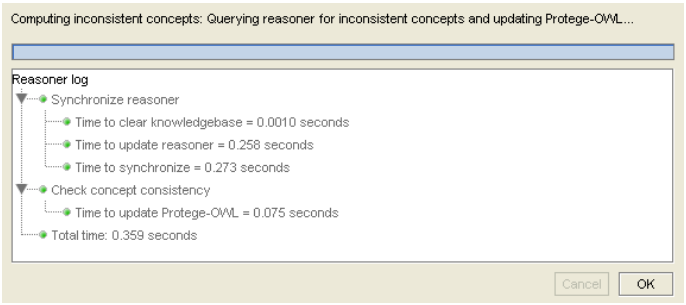

Figure 5.8: *Consistency Check for the GRACE Ontology using the Pellet tool .*

A second test can be accomplished by submitting the ontology to an OWL Validator, to check the ontology compliance with the W3C standard, the validation report is is on the Figure 5.9.

A third validation can be achieved in a manual way, by instantiating the ontology concepts for a particular case study, to support the validation of the ontology correctness and the detection of missing or misunderstanding ontological entities. In order to achieve a better understanding, the instantiation will be presented by analysing separately different parts of the ontology model, i.e. different fragments.

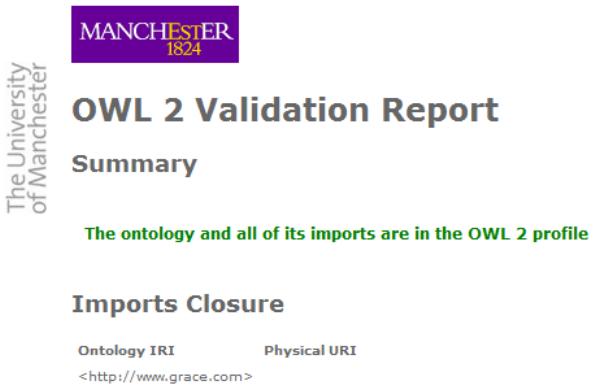

Figure 5.9: *OWL 2 Validation Report for the GRACE ontology .*

Figure 5.10 illustrates two different instances of the class "*Product*", i.e. the product "*_859201049010_0000*" and the product "*_859201049011_1111*", representing two different product models that can be produced in the production line.

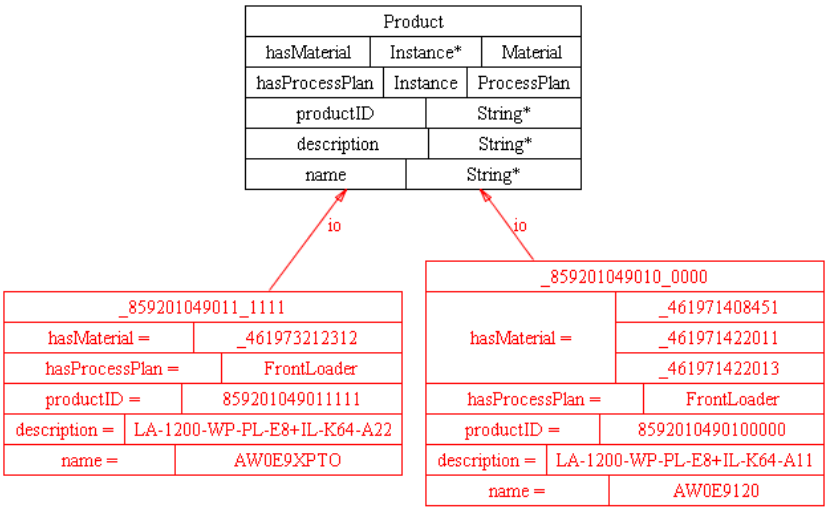

Figure 5.10: *Representation of class "Product" and its instances .*

Note that the relation "*io*", represented between the class and the object, means "instance of". The two instances of the product class are filled with the real data in their attributes, e.g. in the case of the instance "*_859201049010_0000*", the DataType attributes name and description are respectively filled with "AW0E9120" and "*LA-1200-WP-PL-E8+IL-K64-A11*",

and the ObjectProperty attribute hasProcessPlan is filled with the link to the "*ProcessPlan*" class "*FrontLoader*".

In a progressive manner, it is possible to analyse more parts of the ontology. Figure 5.11 represents the several instances of the "MaterialFamily" class, namely "RearTub", "Hub", "ABearing", "BBearing", "ShaftSeal" and "CrossPiece". The relation hasMaterial between the "Product" and "MaterialFamily" classes is also defined for the different instances of the "Product" classes. After instantiating the different types of materials, the relationship between the classes was automatically reflected among the objects; e.g. the product "*_859201049010_0000*" has the following materials: "*_461971408451*", "*_461971422013*" and "*_461971422011*".This exercise is followed to the rest of the instances.

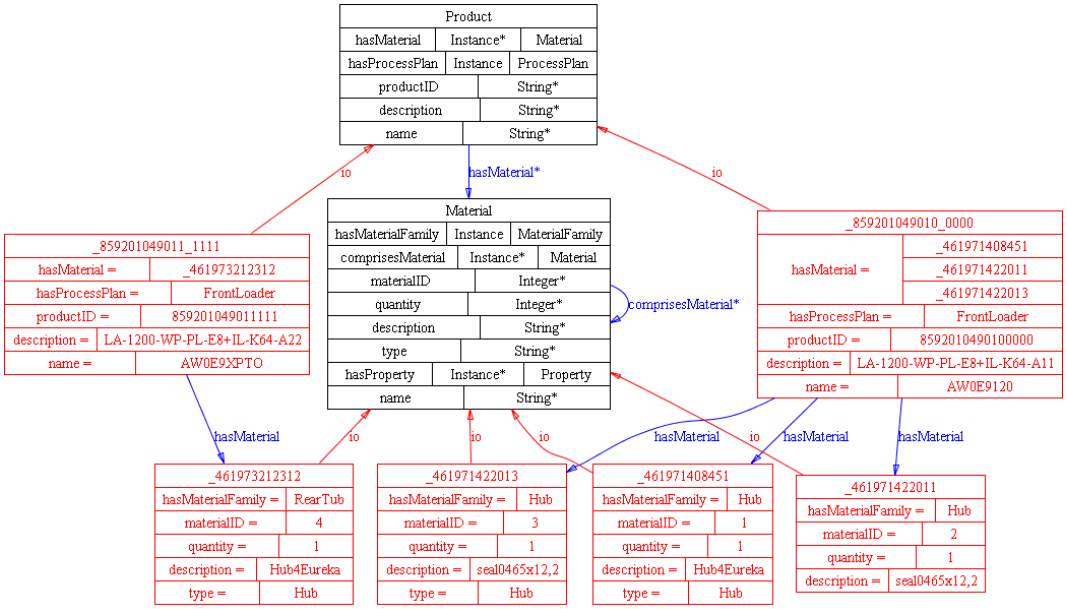

Figure 5.11: *Representation of the "Product" and "Material" classes and their instances .*

The representation of the GRACE ontology classes, their relations and their own instances for this case study is illustrated in the appendix A.4.

Chapter 6

Integration of the Ontology in the GRACE Multi-agent System

The ontology designed plays a crucial role in the GRACE MAS to enable a common understanding among the agents when they are communicating, namely to understand the message at the syntactic level (to extract the content correctly) and at the semantic level (to acquire the exchanged knowledge). This chapter describes the integration of the designed ontology in the developed multi-agent system solution.

6.1 Available Solutions

Since the GRACE multi-agent system is being developed using the JADE, which uses Java, a pertinent question is how to translate the ontology edited and validated in Protégé during the Chapter 5 to be used by the agents developed in JADE. Several options can be considered for this purpose.

The exchange of messages with ontologies structure in JADE normally uses an internal container with a restrict format. Due to the fact that the messages are FIPA compliance, JADE agents are able to interact with other agents, not only from the JADE platform but with different systems. For this purpose, JADE created a reference model along with some notions: *Concept, Agent Action* and *Predicate*.

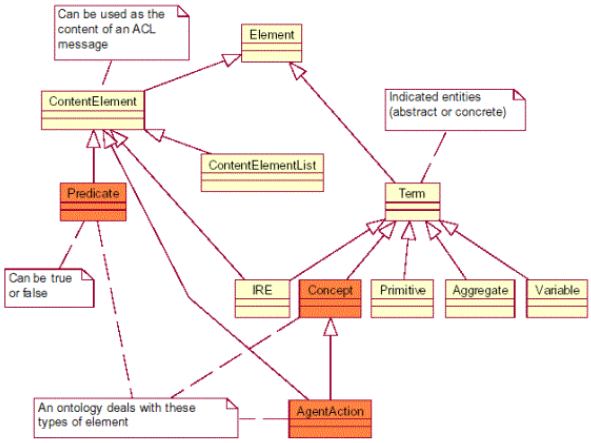

Figure 6.1: *The Content Reference Model [7].*

The key to keep is the ***AgentAction*** that characterizes an action performed by some agent; any act that the agents can perform should be described as Agent Action. When an *AgentAction* is performed, it could generate an effect between the agents, e.g., *sendMessage* or *createProduct*. During the ontology development, all ontological objects should implement one of these interfaces.

There are other terms on Figure 6.1, but the *AgentAction* concept is the most important. When an ontology is created under JADE, it is necessary to derivate the ontology terms from the interfaces. The final result is a model more semantic and expressive for the content language.

In this way, when an ontology is created and integrated in the JADE framework, it is necessary to derivate the ontological terms from the interfaces. The final result is a model more semantic and expressive for the content language.

The integration of the ontology can be performed in two different ways, manually or automatically.

The first one is developing the classes *AgentAction, Concept* and *Predicate* classes by hand, but this process is very difficult and time consuming; the time waste to improve any term and remake the process is very high.

The second option is to use some tools that provide some support do develop automatically

these classes. Figure 6.2 summarizes the several alternatives to translate the ontology into Java classes using automatic tools. Any approach represented in the figure follows the same steps: after the design of the ontology schema, it is necessary to produce the knowledge base. At this stage the ontological schema is supported in the OWL language, being the purpose to create a common shared content.

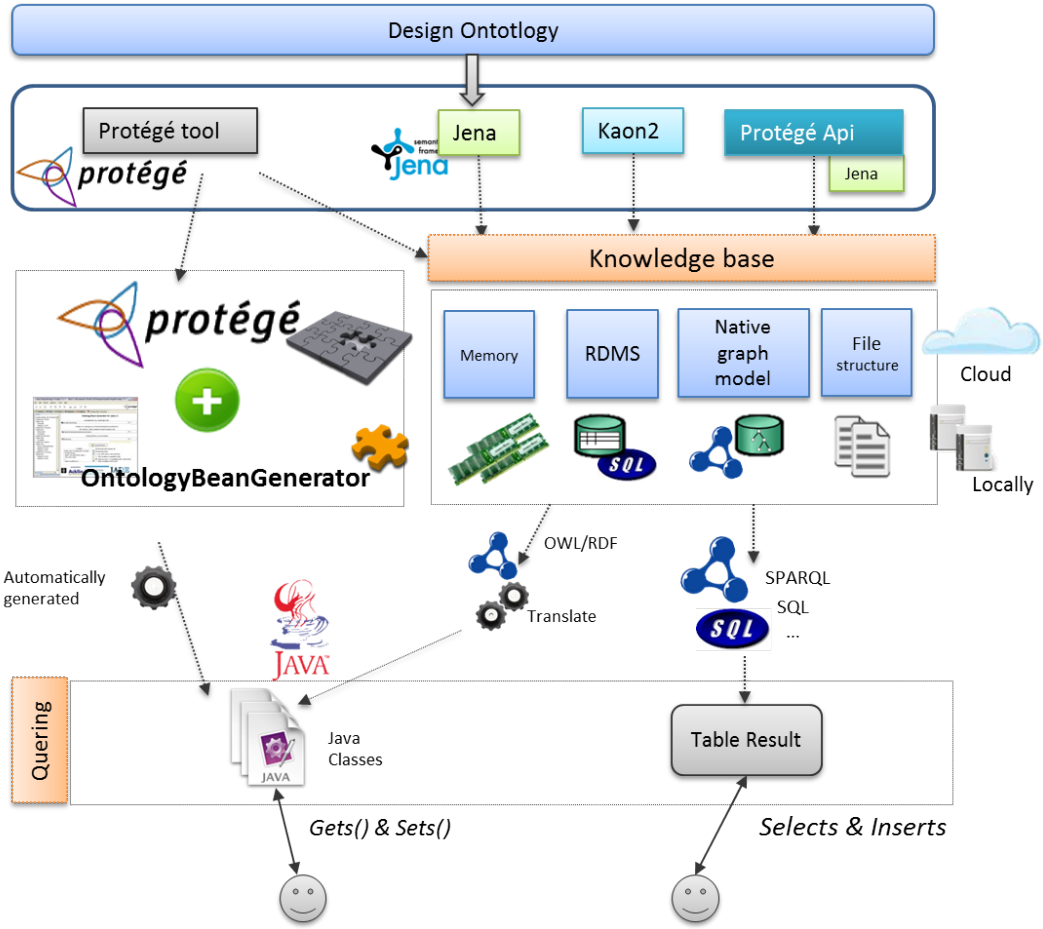

Figure 6.2: *Possible approaches for integration of the ontology in multi-agent systems.*

The presented tools allow the storage procedure in different platforms (memory, text files, databases, etc.). After this, the translation to Java classes can be done, or instead of creating classes, it is possible to use querying tools, such as SPARQL (Protocol and RDF Query Language), to interrogate the ontological model.

One possible approach is to implement the ontology tool in Java through Jena framework. After defining the classes, predicates and constraints it is possible to export to OWL format, and save in several formats locally or remotely on a database. The multi-agent system solution, must use that classes initially created, thus it is necessary to convert the OWL file into Java classes, also the properties in the owl file has a direct relation with the attributes of the classes in Java. This last step can be automated if it is used the plug-in *OntologyBeanGenerator*.

There are several tools to perform automatically the implementation of the knowledge, in this work it is only intended to choose one that best fits the needs and constraints of the scope of this project. It is important to use a tool that facilitates a fast development, in that way a restriction of an interface is important. The exporting process is another important limitation, because if agents cannot use this information, it becomes useless. Figure 6.3 summarizes the comparison of the several tools regarding some aspects to have in consideration when choosing the best tool.

The selection of the alternative that best fits the needs and constraints of this project, must consider issues like the facility to have a fast development and the exporting process. The referred alternatives allow reasoning and data importation from several kinds of databases and also reasoning

Jena is a common framework that can be used in several approaches. It can be used individually, but it is explicitly used as the basis of Protégé API. Moreover, it was building a plug-in for JADE to use OWL files. This plugin, entitled AgentOWL [43], is available on the website of JADE, and uses pure OWL files. Analysing the figure the one that best fits the requirements of this project is the Protégé Bean Generator + Protégé (second case). The Protégé offers an export to different formats (RDF, OWL, etc.), by adding the Protégé plugin an exportation to Java classes is offered.

However, this approach has some disadvantages, namely the loss of flexibility in multi-agent systems, because this approach loses the rationalization of new facts and new rules that will have to be in the ontology, with advanced methods, such as Java Reflexion or Jess (rule engine for the Java platform). If an approach that works with OWL is chosen, the tool can run an inference engine with a set of rules, for example expressed in SWRL (Semantic Web Rule Language) and SPARQL (with inserts). But for this work, this kind of transformation

Program /API	Allow Import from diverse DB	Good User Interface	Plug-Ins	Get Information	Export Formats	OverAll Result
Protégé	Yes	Yes	YES	Need to be exported	XML, RDF, RDFS, OWL, n-triple	Easy to Work
Protégé+ Bean Generator	**YES**	**YES**	**YES**	**The plugin offers a tool to export directly to Java Classes**	**XML, RDF, RDFS, OWL, n-triple**	**Easy to Work, the creation of the classes is automatically, the changing is very easy**
JENA (SPARQL)	YES	NO, It's a Java API	NO	SPARQL, needs to handle the results like SQL result	XML, RDF, RDFS, OWL, n-triple	Getting data form the knowledge base became difficult
JENA (Classes)	YES	NO, It's a Java API	NO	Classes, get the information from the objects	XML, RDF, RDFS, OWL, n-triple	Changing the Schema and knowledge base take some time
KAON2 (Classes or SPARQL)	YES	NO, It's a Java API	NO	SPARQL, needs to handle the results like SQL result	XML, RDF, RDFS, OWL, n-triple	Getting data form the knowledge base became difficult
Protégé API (Classes or SPARQL)	YES	NO, It's a Java API	Yes and No, because it does not have GUI, it becomes difficult to use the plugins	Classes, get the information from the objects	XML, RDF, RDFS, OWL, n-triple	-

Figure 6.3: *Comparison of several tools to implement the GRACE ontology.*

"on-the-fly" is not needed.

6.2 Bean Generator Plug-in

The integration of the ontology can be done without any tool as previously referred. However, using the *OntologyBeanGenerator* plug-in in the Protégé tool, the integration of the ontology

in the multi-agent system solution is much faster. This requires the implementation of the following steps:

1. Include/Import the JADE abstract ontology into the Protégé.

The first step is related to add the schema of the *Abstract Ontology* to the current ontology designed on Protégé tool, as illustrated in 6.4.

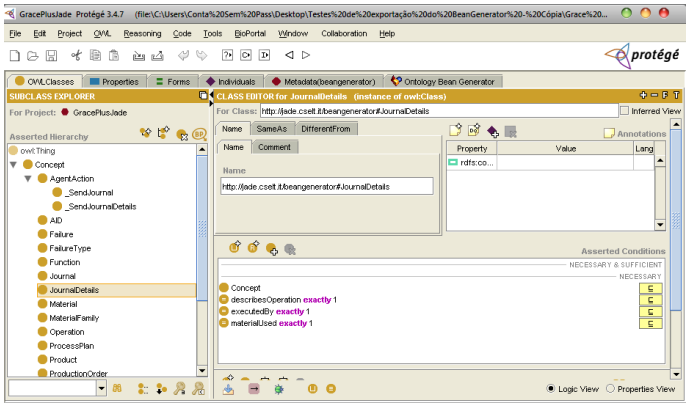

Figure 6.4: *JADE* Abstract Ontology *for OntologyBeanGenerator.*

Looking at Figure 6.4, some of the classes, such as *Concept, Predicate* and *AgentAction* that have already been defined can be noted. These classes or abstract models may be based on frames or OWL language. Therefore the classes that are defined in the project *SimpleJADEAbstractOntology.pprj* must be imported, if based on frames; instead, if they are OWL ontologies, the *OWLSimpleJADEAbstractOntology.owl* must be imported.

2. Include/Import the GRACE ontology into the same Protégé project.

As second step, it is necessary to import the ontology designed for a specific domain. At this moment it is necessary to create new classes, which will support new concepts, such as *AgentAction*.

Initially, an ontology was created without knowing the selected way for the implementation, but at this moment it is necessary to refine the resulted ontology. Figure 6.5 illustrates a fragment of the resulted matching of the GRACE ontology with the *Abstract Ontology* from the *OntologyBeanGenerator*.

3. The next step is related to export the ontology Java classes, which can be done using several options as illustrated in Figure 6.6.

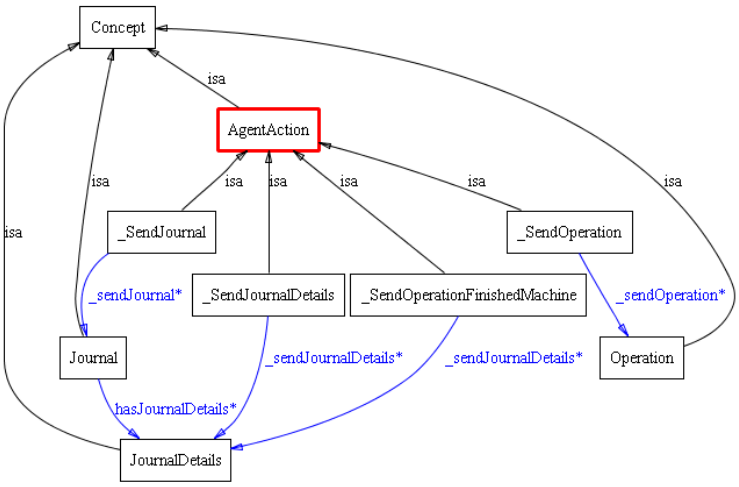

Figure 6.5: *Partial view of the GRACE ontology with* OntologyBeanGenerator *Concepts*

The available options are:

- J2ME: in the case the multi-agent system will run under an embedded system.
- J2SE (standard edition): in case the multi-agent system will run under a normal computer or smartphones (note that this option is compatible with the lighter version of JADE, named the JADE-LEAP).
- J2SE Java Bean: applied for cases similar to the previous one, but using JavaBeans[1]. It is also compatible with JADE.. It is also compatible with JADE.

Another option provided by the plug-in is the creation of a factory pattern, which is a programming design pattern, but no longer makes sense.

4. Import the ontology to be ready to be used.

After the exportation of the ontology, it is sometimes necessary to refine the exported Java classes by hand, due to some syntax errors and wrong reference class introduced during the automatic generation process.

Formerly the ontologies were built using the *Ontology Frames* plug-in, which was a stable version and not introducing errors in the generation process. However, in this work, the

[1]A JavaBean is a Java Object that is serializable, and allows access to properties using getter and setter methods

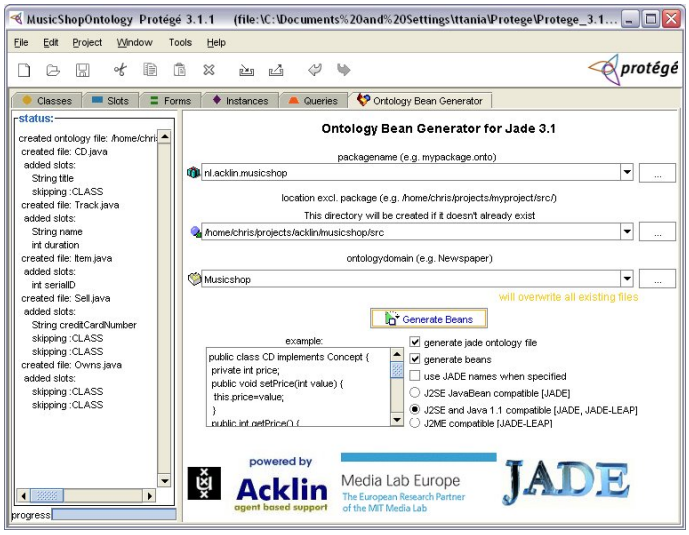

Figure 6.6: *Screen view of* OntologyBeanGenerator *for JADE.*

ontology was developed in the OWL language and consequently the proper plug-in for this kind of representation is the *OWLSimpleJADEAbstractOntology*, which does not provide the same correct results as the former one.

6.3 Implementation of the generated classes

In this work, the GRACE ontology was translated using the OntologyBeanGenerator plug-in to several Java classes as illustrated in Figure 6.7.

The first generated class is the *GraceOntology*, which represents the vocabulary and main concepts defined in the ontology. The following piece of code represents this class:

```
public class GraceOntology extends jade.content.onto.Ontology{
  // Concepts ================== Vocabulary ============================
  public static final String _SENDJOURNALDETAILS__SENDJOURNALDETAILS
     = "_sendJournalDetails";
  public static final String _SENDJOURNAL = "_SendJournal";
  public static final String _SENDOPERATION__SENDOPERATION="_sendOperation";
  public static final String _SENDOPERATION="_SendOperation";
  ...
```

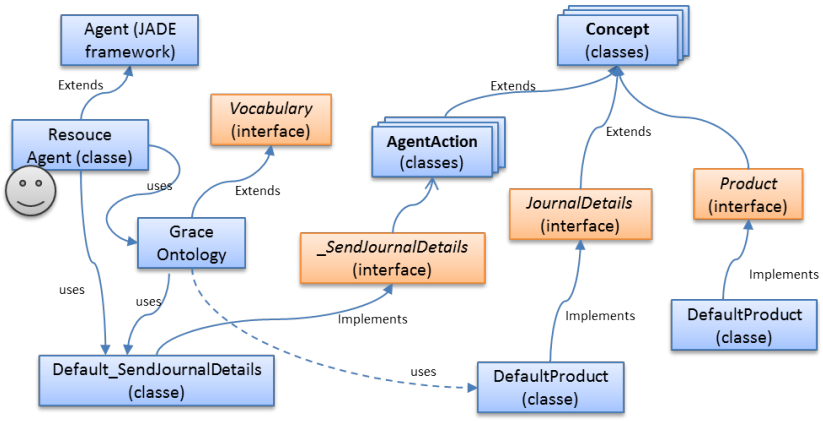

Figure 6.7: *Example some concepts generated by* OntologyBeanGenerator *plus Resource Agent.*

```
private static final long serialVersionUID = 6907737088184824236L;
// A symbolic constant, containing the name of this ontology.
public static final String ONTOLOGY_NAME = "GRACE";
// The singleton instance of this ontology
private static Ontology theInstance = new GraceOntology();
public static Ontology getInstance(){
   return theInstance;
}
private GraceOntology(){
   super(ONTOLOGY_NAME, BasicOntology.getInstance());
   try {
        // ----- adding Concept(s)
        ConceptSchema resourceSchema = new ConceptSchema(RESOURCE);
        add(resourceSchema, DefaultResource.class);
        ConceptSchema qualityControllerSchema = new ConceptSchema(QUALITYCONTROLLER);
        add(qualityControllerSchema, DefaultQualityController.class);
        ...
        // ----- adding AgentAction(s)
        add(_SendOperationFinishedMachineSchema,
                    Default_SendOperationFinishedMachine.class);
        AgentActionSchema _SendOperationSchema =
                    new AgentActionSchema(_SENDOPERATION);
        add(_SendOperationSchema, Default_SendOperation.class);
```

```
            AgentActionSchema _SendJournalSchema =
                        new AgentActionSchema(_SENDJOURNAL);
            ...
            // adding fields
            resourceSchema.add(RESOURCE_HASPROPERTY, propertySchema,
                 0, ObjectSchema.UNLIMITED);
            resourceSchema.add(RESOURCE_LOCATION, (TermSchema)
            getSchema(BasicOntology.STRING), 0, ObjectSchema.UNLIMITED);

            _SendOperationFinishedMachineSchema.add(
                 _SENDOPERATIONFINISHEDMACHINE__SENDJOURNALDETAILS,
            journalDetailsSchema, 0, ObjectSchema.UNLIMITED);
            _SendOperationSchema.add(_SENDOPERATION__SENDOPERATION, operationSchema,
                 0, ObjectSchema.UNLIMITED);
            ...
        }
    }
}
```

This class has a singleton instance. This software design pattern allows restricting the instantiation to only one object. This pattern is needed because of the coordination across the distributed system.

Additionally this class comprises four main parts. The first one is related to the vocabulary defined by the ontology, which comprises the establishment of the constants based on the concepts. The second part is related to adding the list of Concepts, e.g. the quality controller and resource concept schemas. The third part is related to adding the *AgentAction* objects and the last part is related to the restrictions of the previous objects. Any restriction added on the ontology will have a direct translation to one of these several options, i.e. the minimum cardinality, the limitation, the optional/mandatory role, among others. If the validation on the content expression is not the correct one, an exception is thrown.

The second group of generated classes are related to the Java classes that specify the structure and semantic of the ontological objects, namely Concepts and AgentAction classes, and also included in the GRACEOntology package.

The second part is related to adding the list concepts, e.g. quality controller and resource

concept schema.

The Concept classes, such as *Journal, JournalDetails, Resource, Material, ProcessPlan* and *Operation*, are created by extending the class jade.content.Concept. The next code represents the interface of the Journal Concept

The third part is related to adding the *AgentAction* objects and the last is the restrictions of the previous objects, adding the restrictions. Any restriction added on the ontology will have a direct translation or to this several options, i.e. the minimum cardinality, if it is unlimited, optional, or mandatory, among others. If the validation on the content expression is not the correct one exception is thrown.

```
public interface Journal extends jade.content.Concept {
public void addJournalID(String elem);
public boolean removeJournalID(String elem);
public void clearAllJournalID();
public Iterator getAllJournalID();
public List getJournalID();
public void setJournalID(List l);
public void addStartDate(String elem);
public boolean removeStartDate(String elem);
```

All the methods included in this kind of classes to manipulate the attributes of the class should be declared. Some considerations in this approach must be taken: it is possible to declare all the attributes and then the setter and getter methods, but making this class as an interface can provide additional benefits.

In fact, previously, the OntologyBeanGenerator plug-in allowed the exportation of the designed ontology to pure Java classes by creating the getter and setter methods. The developers have noted the advantage of using interfaces in Java. Since the OntologyBeanGenerator plug-in is implemented in Java, it was decided to join these two concepts. Briefly, interfaces serve as a contract, where can be specified which methods and classes are required to be implemented. For two objects communicate, only one need to know the interface of the other. Anything beyond that leads to redundant issues. Therefore, the export interfaces for the specific and subsequently implemented class, creates a rigid environment, consistent with all

good programming practices. The next piece of code illustrates the implementation of the interface for the Journal Concept.

```
public class DefaultJournal implements Journal {
private String _internalInstanceName = null;
private List journalID = new ArrayList();
public DefaultJournal(){
  this._internalInstanceName = "";}
public DefaultJournal(String instance_name) {
  this._internalInstanceName = instance_name;}
public void addJournalID(String elem) {
  journalID.add(elem);}
public boolean removeJournalID(String elem) {
  boolean result = journalID.remove(elem);
  return result;}
```

The AgentAction classes are classes representing the actions performed by the agents, and are for example _SendJournal, _SendJournalDetails, _SendOperation and _SendOperationFinishedMachine. Each class of the type AgentAction is represented by extending the jade.content.AgentAction class. The next code represents the action _SendJournal.

```
public interface _SendJournal extends jade.content.AgentAction {
  // Protege name: http://jade.cselt.it/beangenerator#_sendJournal
  public void add_sendJournal(Journal elem);
  public boolean remove_sendJournal(Journal elem);
  public void clearAll_sendJournal();
  public Iterator getAll_sendJournal();
  public List get_sendJournal();
  public void set_sendJournal(List l);
}
```

In the same way as occurred for the Journal Concept, it is also necessary to declare the implemented class *Default_SendJournal* for the Interface *_SendJournal*. At this stage, all classes needed for the ontological model are created. However, as previously referred, some hand-made corrections were required due to the error of the used plug-in.

The resulted implemented ontology (i.e. the generated classes) is now ready to be used by the GRACE agents.

6.4 Usage of the GRACE Ontology

The use of the Java classes (which represents the ontology) by the agents closes the several phases of the development of the GRACE ontology, started with the conceptualization, passing by the specification of the ontology schema and followed by its validation and implementation. Figure 6.8 illustrates the use of the ontology (generated from the ontology schema edited in Protégé and using the OntologyBeanGenerator plug-in) to support the interaction among distributed agents, where the agents use the same ontology (but different fragments of the ontology) to express the shared knowledge that is exchanged.

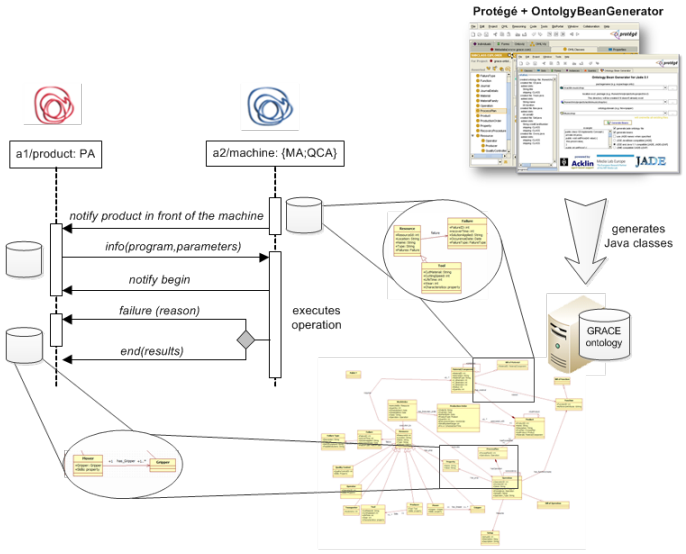

Figure 6.8: *Agents using ontologies to exchange knowledge.*

The use of the ontology expressed in the Java classes by the agents, requires the registration the ontology on the system, according to the selected codec. This process is necessary to be executed only once in each agent that will send or receive ontological messages.

Any codec has as purpose to support the language, in order to maintain the correct semantics and expression of terms. JADE has two basic types of codecs as a content of language, the SL codec and the LEAP codec.

When exporting through the OntologyBeanGenerator plug-in, the possibility to choose is given. This decision is made by the developer, choosing one of the two codecs. LEAP is

more lightweight, but on the other hand, the content is more readable in SL. It can be said that LEAP is to be read and interpreted by computers, while the content of SL language structure is human readable. So the main key to keep is to only use LEAP when there are strong memory limitations. It would be possible to choose a codec to support an XML-based, or even if it is the developer interests to implement its language, requiring a codec for it.

In this work, it is used LEAP and the next program illustrates how to register the ontology on the agents' behaviours.

```
class WaitingMessages extends CyclicBehaviour implements IConstants, IConstants_GUI {
...
private Codec codec = new LEAPCodec();
//or private Codec codec = new SLCodec();
private Ontology ontology = GraceOntology.getInstance();
WaitingMessages(Agent aThis, boolean myGuiON, formRA_ myGui){ ... }

@Override
public void action()
{
  // Register language and ontology
  myAgent.getContentManager().registerLanguage(codec);
  myAgent.getContentManager().registerOntology(ontology);
  ACLMessage msg = myAgent.receive();
```

Having registered the ontology, the agents can start using the ontology to represent the knowledge and also to send messages containing this knowledge. Considering the example of exchanging a message, several steps should be considered.

First, it is necessary to create the ontological message and send it. The next piece of code illustrates how to create an ontological message structure and send it to other(s) agent(s). In this case, a PA agent sends a message to a RA.

```
//ONTOLOGY
//implementacao do _SendOperation
GRACE_Ontology.Operation operation = new DefaultOperation();
operation.addDuration(1); operation.addName(op.getOperation());
//action _SendOperation sendOperation = new Default_SendOperation();
```

```
sendOperation.add_sendOperation(operation);
sendOntologyMessage(RA_RECEIVES_PROCESS_PLAN, msg.getSender(),
sendOperation, ACLMessage.INFORM);
...
private boolean sendOntologyMessage(int KONSTANTE, AID receiver,
AgentAction action, int performative){
ACLMessage msg = new ACLMessage(performative);
msg.setLanguage(codec.getName());
msg.setOntology(ontology.getName());
try {
msg.addReceiver(receiver);
msg.setConversationId(((Integer) KONSTANTE).toString());
myAgent.getContentManager().fillContent
(msg,new Action(receiver, action));
myAgent.send(msg);
...
```

The key issue here is to fulfil the message attribute, namely the *setOntology()* and *setLanguage()* methods, and use the *FillContent()* method to fulfil the content of the message using the desired ontological object representing the knowledge that PA wants to exchange.

The second step is related to receive the ontological message and parse it. To properly receive the message, the agent needs to extract the contents with the *extractContent()* method. The extracted content of the message is then parsed by comparing the instance type with the type of value that is expected. In the following piece of code, the result of "if-then" tests determines which type of instance is the content of the message.

```
ContentElement content = null;
try {
  content = myAgent.getContentManager().extractContent(msg);
  Concept action = ((Action) content).getAction();
  if (action instanceof _SendOperation) {
    _SendOperation sendedOperation = (_SendOperation) action;
    GRACE_Ontology.Operation operation =
        (GRACE_Ontology.Operation)sendedOperation.get_sendOperation().get(0);
    journalDetails.setName(myAgent.getLocalName());
    ...
```

In Figure 6.9 it is possible to see an example of the sequence of messages exchanged between agents.

1) The RA agent "*A_Bearing_Insertion*" receives the notification that the product is in front of the machine.

2) The RA agent sends a message to the PA agent "*011210007041*", notifying that the product is ready to be executed.

3) The PA agent sends to the RA agent a message containing the information regarding the operation.

4) The RA, sends a message to the IMA, notifying the start of the operation execution.

5) The RA agent informs the PA that the operation is already finished.

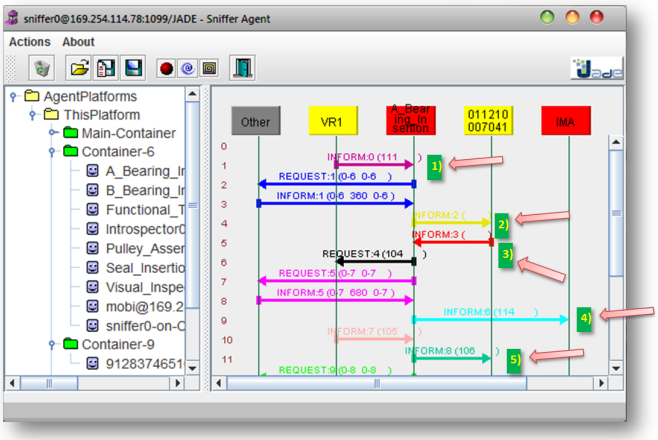

Figure 6.9: *Excerpt from the process of sending the Processplan of PA to RA agent.*

At the moment 3) of Figure 6.9, the PA agent sends the notification to the RA agent to execute the operations.

Figure 6.10 illustrates the content (structured as an ontology and not as string) of the exchanged ACL message between the PA and RA related to the moment 3).

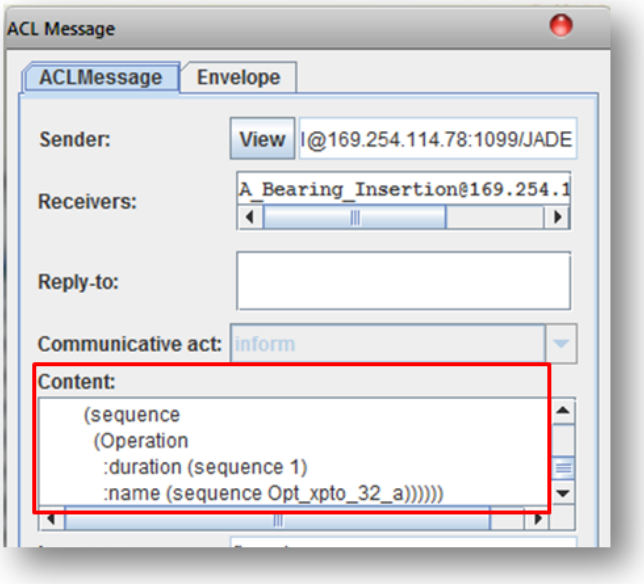

Figure 6.10: *ACL message exchanged between PA and RA agents.*

The content of the ACL message sent by the PA to RA requesting for an execution of the operation is illustrated as following.

```
((action
(agent-identifier
  :name A_Bearing_Insertion@169.254.114.78:1099/JADE
  :addresses (sequence http://Ricardo-PC:7778/acc))
  (_SendOperation
    :_sendOperation
    (sequence (Operation :duration (sequence 1)
      :name (sequence Opt_xpto_32_a))))))
```

The response to this ACL message, also captured by the sniffer tool from the JADE framework, is illustrated as follows.

```
((action
(agent-identifier
:name "011210007041@169.254.114.78:1099/JADE"
:addresses (sequence http://Ricardo-PC:7778/acc))
```

```
(_SendOperationFinishedMachine
  :_sendJournalDetails
  (sequence (JournalDetails
    :startDate (sequence "Mon Mar 12 06:07:59 GMT 2012")
    :startTime (sequence "6:7:59")
    :endTime (sequence "06:08:04")
    :overallResult (sequence "1")
    :productID (sequence "011210007041")
    :endDate (sequence "2012-03-12")
    :name (sequence A_Bearing_Insertion))))))
```

This example makes obvious the reason to use ontologies to represents the shared knowledge, because the agent which receives a message from another agent, must possess the schema to perform the parsing. These terms are no longer simple words and start to have semantic meaning.

Chapter 7

Conclusions and Future Work

The initial objective of the described work is the development of an ontology integrating the quality and process control for a production line producing washing machines, to be applied in a multi-agent infrastructure developed for the case. This ontology aims to represent the knowledge associated to the washing machines production lines domain.

This document accomplishes the last step of the ontologies development process, i.e. the documentation. It is important that a design ontology has a good documentation support, which explains in a very simple manner some of the reasons and assumptions taken during the phases of the development of the ontology. The selected concepts, terms and relationships should be clarified and documented, because some of the terms could be very common and represent different meanings.

7.1 Conclusion

During this work it was developed a MAS application, to help in this development it was used the JADE framework. It was also specified ontology to represent the knowledge of the case study, this specification was developed in Protégé. Finally was integrated the ontology developed in the system, in order to the agents being able to use the knowledge and share it among them self. The integration was performed using a plug-in, which accelerates the process of integration.

This work is relevant, because it aims to contribute to the implementation of such systems in industrial environments.

However, it is important to refer some of the problems encountered.

The inexistence of a single standard for the ontology was one of the problems, it was expected to reuse an already present ontology, however it was not possible due to the particularly of the domain, which required to create a new one re-using some ontological concepts from existing ontologies. The several meetings with the production line owner allowed considering advices and obviously the know-how of the concepts, contributing for the correct construction of the ontology.

The second problem was related to the choice of the approach to be taken for the implementation of the system. In this work, the OntologyBeanGenerator plug-in was used due to its capability to simplify the implementation process. However, a problem has been found in the exportation of the last version of the OntologyBeanGenerator plug-in, which was not performed correctly. Becoming unthinkable to use the old version of the plug-in, it was necessary to correct it by hand.

The application of this embebed ontology on multi-agent systems to a real-world industrial application at a production line producing washing machines, will contribute for a proof-of-concept and a wider adoption of this technologies in industry (MAS and ontologies). The project ends with an integrator character, since the present study of acquired competencies has an added value when introduced in real world.

7.2 Future Work

The work described in this document is not a closed cycle and after the implementation of the designed solution in a real case, it is necessary to move on because in a constant evolution field there are always open points.

The first possibility for future work is to create an easy and suitable interface inside the GRACE MAS infrastructure, to enable the ontology expert's domain to modify the ontology without the need to interact with ontology engineers, and without the need to know large technical details, particularly for the ontology instantiation in order to verify and validate the ontology problems.

Another possible work to do in the future is to change the processes of using the ontology within the MAS system, in order to infer new knowledge, without having to change the engineering process again.

Developing a methodology for mapping components that enter the database Bill Of Materials with processes of ontology. Enhance the ontology to stop giving sustenance to the knowledge of agents, but for providing services, directing the work into the area of Ontology-Services in the MAS system.

Any of these referred hypotheses will help to improve and create a system model more flexible.

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Appendix A

GRACE Ontology Description

Any of these hypotheses, will help to improve and create a system model more flexible and mouldable .

A.1 Relations or Predicates

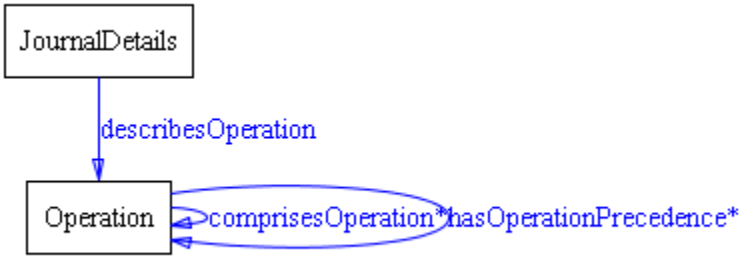
comprisesMaterial This predicate establishes the recursive relation between the class "Material", meaning that a material or component consists of other materials (in a certain quantity) according to the BOM structure, being formally defined as follows:

- *comprisesMaterial* $(x, y)$the material x uses the material y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Material.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Material.

Note that R and C intend to represent the Property of the relations.

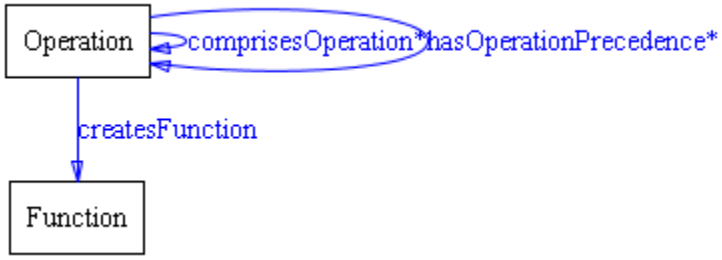
comprisesOperation This predicate establishes the recursive relation between the class "Operation", meaning that an operation can be decomposed into several sub-operations, being formally defined as follows:

- *comprisesOperation* (x, y) an operation x contains operation y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Operation.



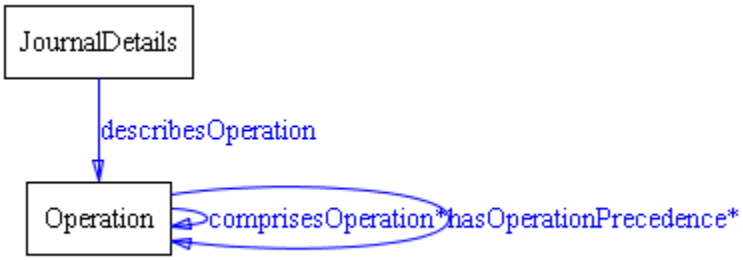
createsFunction This predicate establishes the relation between the class "Operation" and the class "Function", allowing creating a function from the execution of an operation using a material, being formally defined as follows

- *createsFunction* $(x, y)$the operation x creates the function$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Function.



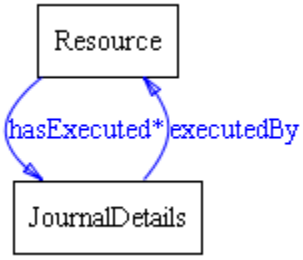
describesOperation This predicate establishes the relation between the class "JournalDetails" and the class "Operation", meaning that the details about the execution of the operation are reported in the journal details, being formally defined as follows:

- $executedBy(x, y)$journal details x describes the execution of the operation y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the JournalDetails.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Resource.



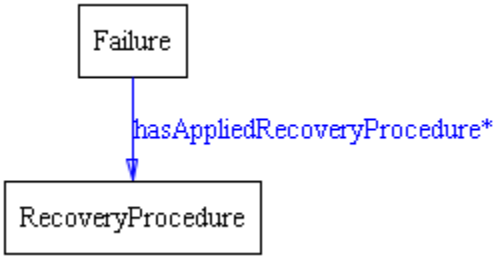
executedBy The predicate *executedBy* establishes the relation between the class "*JournalDetails*" and the class "*Resource*", describing the resource that was executed the operation described in the journal details, being formally defined as follows:

- *executedBy*$(x, y)$the operation described in the journal details x was executed by the resource$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the JournalDetails.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Resource.



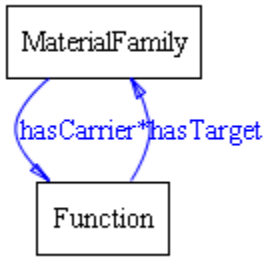
hasAppliedRecoveryProcedure This predicate establishes the relation between the class "Failure" and the class "RecoveryProcedure", describing the recovery procedure applied to solve the occurred failure, being formally defined as follows:

- *hasAppliedRecoveryProcedure* (x, y) the recovery procedure y was applied to solve the failure x.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Failure.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the RecoveryProcedure.



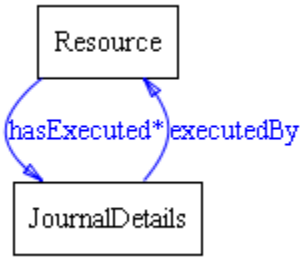
hasCarrier This predicate establishes the relation between the class "Function" and the class "MaterialFamily", meaning that the specified material family component is delivering a function, i.e. a material family is designed to provide one or more specific functions to other material family or to external environment, being formally defined as follows:

- *hasCarrier*$(x, y)$the function x is carried by the material family y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is Function.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the MaterialFamily.



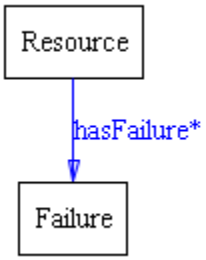
hasExecuted This predicate establishes the relation between the class "Resource" and the class "JournalDetails", describing the list of operations executed by a specific resource during its production history, being formally defined as follows:

- *hasExecuted*$(x, y)$the resource x has executed the operation described in the journal details$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Resource.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the JournalDetails.



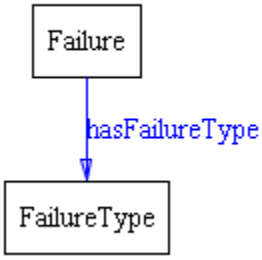
hasFailure This predicate establishes the relation between the class "Resource" and the class "Failure", meaning that failures can occur during the execution of operations by a resource, being formally defined as follows:

- *hasFailure* (x, y, t)a failure y occurred in resource x at time t.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Resource.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Failure.



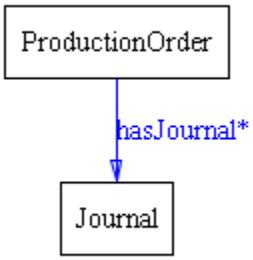
hasFailureType This predicate establishes the relation between the class "Failure" and the class "FailureType", meaning that a failure occurrence is from a specific type of failure, being formally defined as follows:

- *hasFailureType*(x, y)a failure x belongs to the failure type$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Failure.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the FailureType.



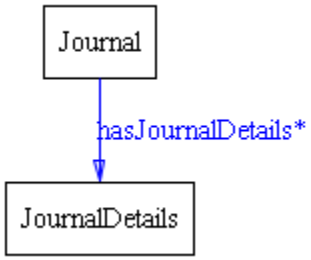
hasJournal This predicate establishes the relation between the class "ProductionOrder" and the class "Journal", meaning that a journal is the description of the execution of a product item defined in the production order, being formally defined as follows:

- *hasJournal* (x, y): a production order x comprises the production of several product items, each one described by the journal$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the ProductionOrder.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Journal.



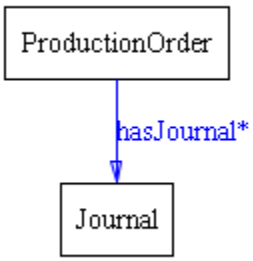
hasJournalDetails This predicate establishes the relation between the class "Journal" and the class "JournalDetails", meaning that the journal details describes the execution of the operation belonging to the process plan during the execution of a product item defined in the production order. It is formally defined as follows:

- *hasJournalDetails* (x, y): journal x describes the execution of a product item, comprising the execution of several operations, each one described by journal details$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Journal.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the JournalDetails.



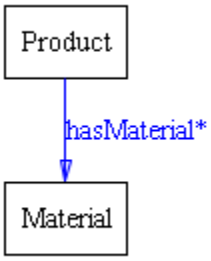
hasJournal This predicate establishes the relation between the class "ProductionOrder" and the class "Journal", meaning that a journal is the description of the execution of a product item defined in the production order, being formally defined as follows:

- *hasJournal* $(x, y))$: a production order x comprises the production of several product items, each one described by the journal$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the ProductionOrder.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Journal.



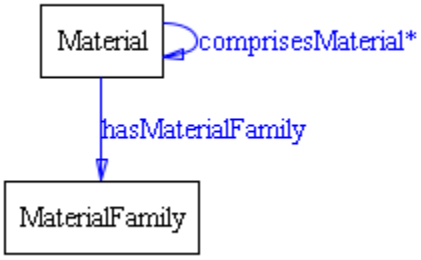
hasMaterial This predicate establishes the relation between the class "Product" and the class "Material", meaning that a product consists on a set of materials according to the BOM, being formally defined as follows:

- $hasMaterial(x, y)$: product x has the material y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Product.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Material.



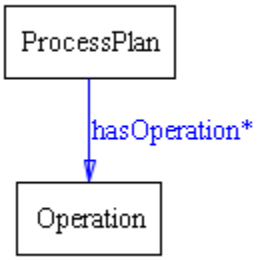
hasMaterialFamily This predicate establishes the relation between the class "Material" and the class "MaterialFamily", meaning that a material is from a material family (i.e. a type of material), being formally defined as follows:

- *hasMaterialFamily* (x, y): material x is from the material family$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Material.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the MaterialFamily.



hasOperation This predicate establishes the relation between the class "ProcessPlan" and the class "Operation", defining the list of operations required to execute a product model, being formally defined as follows:

- *hasOperation* (x, y): a process plan x contains operation y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the ProcessPlan.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Operation.

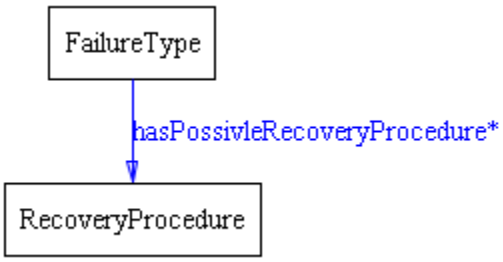


hasOperationPrecedence This predicate establishes the recursive relation between the class "Operation", defining a precedence to execute an operation, i.e. meaning that the execution of an operation should only be performed after the execution of other operations. It is formally defined as follows:

- *hasOperationPrecedence*(x, y): the execution of operation x requires the previous execution of operation y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Operation.

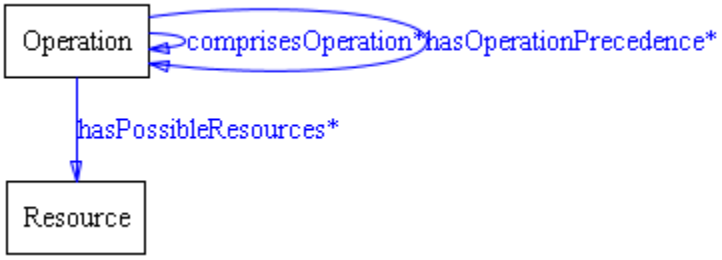
hasPossibleRecoveryProcedures This predicate establishes the relation between the class "FailureType" and the class "RecoveryProcedure", describing the list of possible recovery procedures that can be applied to solve a failure event type, being formally defined as follows:

- *hasPossibleRecoveryProcedures* (x, y): the failure type x can be solved by applying the recovery procedure$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the FailureType.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the RecoveryProcedure.



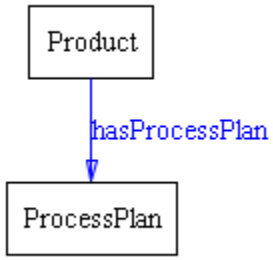
hasPossibleResources This predicate establishes the relation between the class "Operation" and the class "Resource", meaning that there is a list of potential resources that are able to execute the operation, being formally defined as follows:

- $hasPossibleResource(x, y)$: resource y is a candidate for the execution of the operation$x$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Resource.



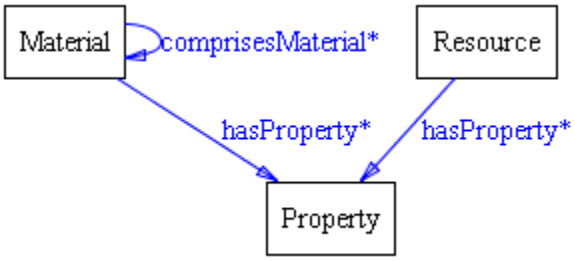
hasProcessPlan This predicate establishes the relation between the class "Product" and the class "ProcessPlan", meaning that the production of a product model requires the execution of a process plan, being formally defined as follows:

- *hasProcessPlan*(x, y): the production of product x requires the process plan y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Product.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the ProcessPlan.



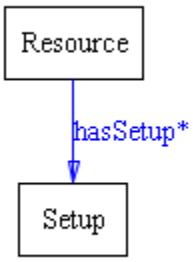
hasProperty This predicate establishes the relation between the class "Resource" and the class "Property" or between the class "Material" and the class "Property", meaning that a resource has a set of skills that allow it to execute operations or that a material has a set of attributes. It is formally defined as follows:

- *hasProperty*(x, y): resource or material x has the property (skill) y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is Resource or Material.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Property.



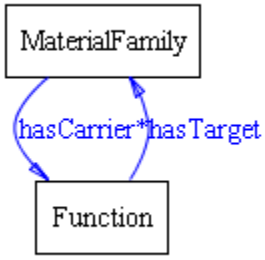
hasSetup This predicate establishes the relation between the class "Resource" and the class "Setup", meaning that a resource may have different setups that will allow the execution of different operations, being formally defined as follows:

- *hasSetup* (x, y): resource x has the setup$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Resource.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Setup.



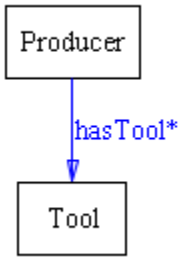
hasTarget This predicate establishes the relation between the class "Function" and the class "MaterialFamily", meaning that one material family component is receiving a function. It is formally defined as follows:

- *hasTarget* (x, y): function x has target of material family y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Function.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the MaterialFamily.



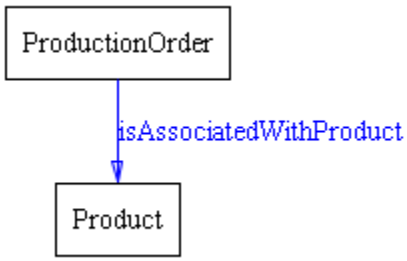
hasTool This predicate establishes the relation between the class "Producer" and the class "Tool", meaning that a producer has a set of tools to execute processing operations, being formally defined as follows:

- $hasTool(x, y, t)$: producer (a specialization from the resource class) x has the tool$y$ available in its internal magazine at time t.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Producer.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Tool.



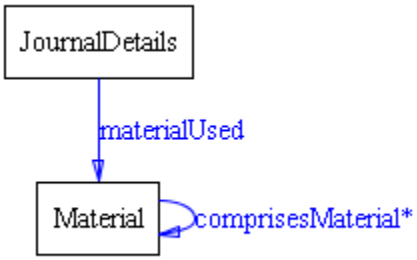
isAssociatedWithProduct This predicate establishes the relation between the class "ProductionOrder" and the class "Product", meaning that a production order is related to the production of a certain quantity of an available product model, being formally defined as follows:

- *isAssociatedWithProduct* (x, y): a production order x is associated to the product y.
- Domain: $\forall x \exists y (R(x, y) \rightarrow C(x))$, where x is the ProductionOrder.
- Range:$\forall x, y (R(x, y) \rightarrow C(y))$, where$y$ is the Product.



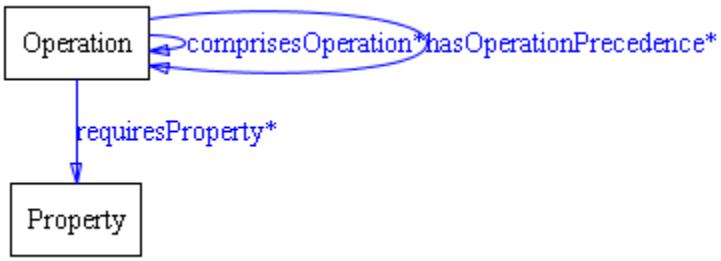
materialUsed This predicate establishes the relation between the class "JournalDetails" and the class "Material", meaning that a journal details describes the material used to execute an operation, being formally defined as follows:

- *materialUsed* (x, y): journal details x describes that the material y was used to execute the operation.
- Domain: $\forall x \exists y (R(x, y) \rightarrow C(x))$, where x is the JournalDetails.
- Range:$\forall x, y (R(x, y) \rightarrow C(y))$, where$y$ is the Material.



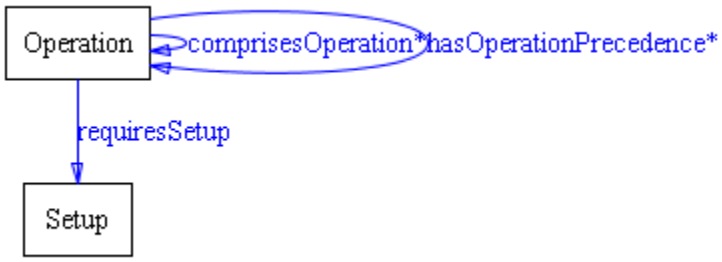
requiresProperty This predicate establishes the relation between the class "Operation" class and the class "Property", meaning that the execution of the operation requires the fulfilment of a set of requirements by potential resources, being formally defined as follows:

- *hasSetup* (x, y): operation x requires the property y to be executed.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Property.



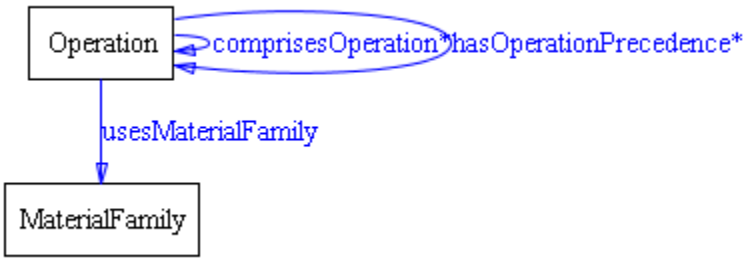
requiresSetup This predicate establishes the relation between the class "Operation" and the class "Setup", meaning that the execution of the operation requires the existence of a proper setup in the resource, being formally defined as follows:

- *requiresSetup* (x, y): operation x needs the setup$y$ to be executed.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Setup.



usesMaterialFamily This predicate establishes the relation between the class "Operation" and the class "MaterialFamily", meaning that the execution of the operation uses a material from a proper family. It is formally defined as follows:

- *usesMaterialFamily* (x, y): operation x uses a material family y.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Operation.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the MaterialFamily.



At this stage, the relations defined in the GRACE schema ontology are identified and described. Later on, in the section related to the restrictions, the description of the relations will be completed by the definition of the type of relation (connection) and the cardinality associated.

A.1.1 Predicates versus Predicates Classes

There is some confusion regarding the design of ontologies, when it is put into the equation the concept of Predicates and Predicate Classes (Predicate Classes it is a design pattern and not concept).

When it is necessary make a relation from a complex type X, to another type Y, it can be made through different process.

The first option is to add the type y in the domain of x. Otherwise add a predicate that relates the two entities.

In the first approach, the Address is related with the Factory through a predicate *haveAddress*

Figure A.1: *Using a predicate to relate both entities.*

For example, looking at the Figure A.1,

- $haveAddress(x, y)$the Factory x has the Address$y$.
- Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Factory.
- Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Address.

With this example, the Factory entity accesses the Address predicate to which is related. The second approach is to add a new entity to serve as intermediary. The Predicate Class supports the creation of a new class to make the role of predicate. As shown in next Figure

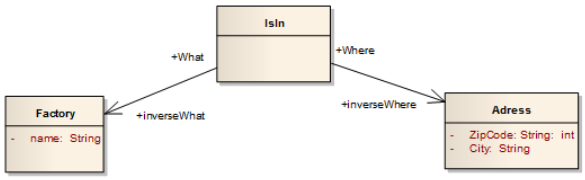


Figure A.2: *Using the Class as predicate to relate both entities.*

Looking Figure A.2 it can be seen that it is necessary to have two predicates in order to make the connection with the new class.

- $inverseWhat(x, y)$the Factory x has the HaveAddressy$y$.
  - Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the Factory.
  - Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the HaveAddressy.
- $inverseWhere(x, y)$the HaveAddressx x has the Address y.
  - Domain: $\forall x \exists y(R(x, y) \rightarrow C(x))$, where x is the HaveAddress.
  - Range:$\forall x, y(R(x, y) \rightarrow C(y))$, where$y$ is the Address.

To access the address with this approach it is necessary to perform a further step in the previous case, which in a larger ontology may become a problem.

The selection about the best approach should be balanced and based on the fact that the ontology will hold static values or not. That is, taking the same example, if the Factory always has the same address, it can and should use a simple Predicate, otherwise, if the value in the Address class is variable, a more mouldable Predicate should be chosen. Following the heuristic rule used in this case a class that represents a property is created. In the case of this project, entities will stay with the same value, being chosen the first approach.

A.2 Attributes

Attributes are values relative to properties of concepts. These values could be *DataTypes* (e.g. string, integer) or *PropertyTypes* (i.e. ontology concepts, e.g. resource and operation,

established as relations). These attributes work like restrictions to the concepts (other types of restrictions will be analysed in the next section). The following Table A.1 defines the main attributes established in the GRACE ontology.

Domain refers to the concept that holds the attribute and the item Range refers to the type of that attribute, e.g. "XSD.Integer" in case of Integer or "XSD.string" in case of String.

Table A.1: *GRACE ontology attributes.*

Attribute	Description	Domain	Range
description	A statement describing something, e.g. a product or a setup	Setup, Product, FailureType, Material MaterialFamily, Operation and RecoveryProcedure	XSD.string
detailedResult	The detailed description of the results obtained in a measurement/ testing operation	JournalDetails	XSD.string
dueDate	The date on which an obligation, e.g. the production of a product, must be accomplished	ProdutctionOrder	XSD.date
earliestDate	The date before which an activity or event cannot start.	ProdutctionOrder	XSD.date
endTime	The date describing the end of the execution of an activity	Journal, Journal Details	XSD.date

Attribute	Description	Domain	Range
expectedDetailedResult	The description of the expected (ideal) result fora function created by the execution of an operation	Function	XSD.string
failureID	A non-negative integer number that provides the unique identification of the failure	Failure	XSD.int
functionType	The type of the failure that can occur during the production execution	Function	XSD.string
journalDetailsId	A non-negative integer number that provides the unique identification of the journal details	JournalDetails	XSD.int
journalID	A non-negative integer number that provides the unique identification of the journal (e.g. could be the serial number identified the produced product item)	Journal	XSD.int
location	A place where something, e.g. a resource, is located	Resource	XSD.string
materialFamilyID	A label that provides the identification of the material family	MaterialFamily	XSD.string

Attribute	Description	Domain	Range
materialID	A non-negative integer number that provides the unique identification of the material	Material	XSD.int
materialType	The type of material to be used in the execution of an operation during the production of a product	Material	XSD.string
mathOperator	The mathematical operator that can establish a comparison in the value of a property	Property	XSD.string
name	The designation of a, thing, e.g. a resource a property or an operation	Resource, Property, Operation, Product, MaterialFamily, Material, Journal, FailureType, Failure, Function, JournalDetails, ProcessPlan, RecoveryProcedure	XSD.string
occurenceDate	The date when a failure occurred	Failure	XSD.date
operationID	A non-negative integer number that provides the unique identification of the operation	Operation	XSD.int
operationType	The type of operation to be executed, e.g. drilling, painting and welding	Operation	XSD.string

Attribute	Description	Domain	Range
overallResult	The overall result obtained in a measurement/testing operation, for example OK or KO	Journal Details	XSD.string
procedureID	A non-negative integer number that provides the unique identification of the recovery procedure	RecoveryProcedure	XSD.int
processPlanID	A non-negative integer number that provides the unique identification of the process plan	ProcessPlan	XSD.int
productID	A non-negative integer number that provides the unique identification of the product	Product	XSD.int
productionOrderID	A non-negative integer number that provides the unique identification of the production order	ProductionOrder	XSD.int
quantity	A positive rational number that defines the specific amount of things to be produced	ProductionOrder, Material	XSD.int
recoveryTime	A positive rational number, it gives the indication of the recovery time after a failure (expressed in seconds)	Failure	XSD.int

Attribute	Description	Domain	Range
setOfSymptons	List of symptoms that may lead to the occurrence of a failure (important to forecast failures and to support the diagnosis)	FailureType	XSD.string
setupID	A non-negative integer number that provides the unique identification of the setup	Setup	XSD.int
startDate	The date describing the start of the execution of an activity	ProductionOrder, Journal Journal Details	XSD.Date
state	The current state of the resource, e.g. waiting, running and broken	Resource, Journal	XSD.string
thisID	A non-negative integer number that provides the unique identification of the resource	Resource	XSD.int
toolType	The type of tool used to perform a processing or handling operation	Tool	XSD.string

Attribute	Description	Domain	Range
type	The designation of a type, e.g. a description. For example, a quality controller could be a vision station or a vibration control station	Resource, Operation, FailureType, Material, Function	XSD.string
unit	The description of the units used to represent the value in the property	Property	XSD.string
value	A specific amount related to a property type	Property	XSD.int

From the analysis of the list of attributes, the concept Property requires a special attention. The tuple {name, value, unit, mathOperator}, associated to the datatype property, represents the properties and characteristics exhibited by a resource or required by an operation to be performed. Examples of properties are:

- LifeTime: a positive rational number that defines the life time of a tool (expressed in seconds).
- Axes: a non-negative integer, e.g. the number of axes of a machine.
- ProcessingType: a type of processing e.g. turning, milling, or drilling.
- Repeatability: a non-negative float, it gives an indication about the degree to which repeated measurements under unchanged conditions show the same results (expressed in mm).
- FeedRate: a positive rational number, it gives the feed rate of a specific axis (expressed in mm/rot).

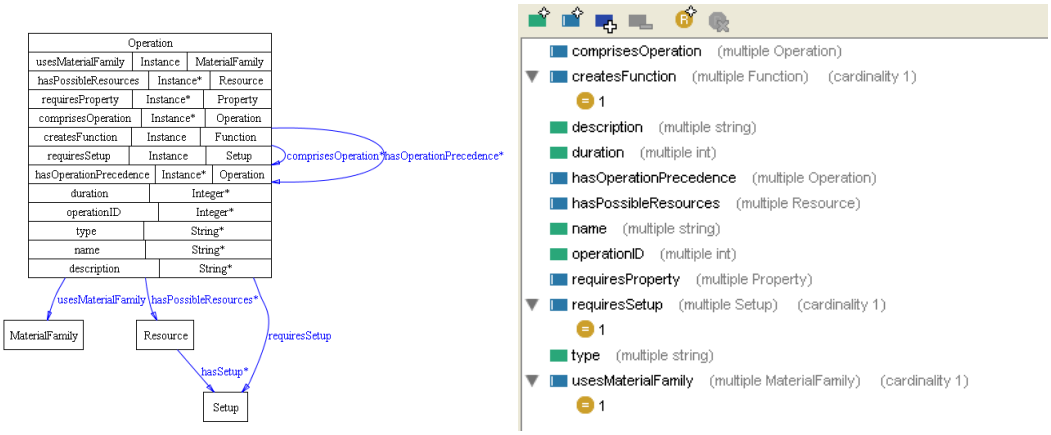
- SpindleSpeed: a range of non-negative integers, it gives the spindle speed in the form [min, max] (expressed in rpm).
- Tailstock: a range of non-negative integers, it gives the size in form [min,max] of pieces that the machine can process (expressed in mm).
- Payload: positive integer, it gives the maximum load of the robot that guarantees the repeatability (expressed in kg).
- MaxReachability: positive integer, it gives the work volume of the robot (expressed in mm).
- MagazineCapacity: non-negative integer, it gives the number of tools or grippers that the magazine of a machine or robot can store.
- CuttingSpeed: a positive rational number, it gives the cutting speed (expressed in mm/s).
- Wear: a positive number defining the wear of a cutting tool (expressed in mm).
- CycleTime: a positive number defining the length of the performed quality control task (expressed in seconds).
- PercentOfScraps: a positive number defining the percentage of scraps identified (referred to the total number of inspected items).

A.3 Constrains/Restrictions

The design of an ontology may consider the restrictions associated to the ontological concepts, restricting the values and the cardinality associated to the identified predicates. The restrictions related to the values are created to implement the obligation of having the relation among concepts, and the restrictions about the cardinality are related to create the obligation in terms of number in those relations. Here, it is also important to consider the restriction in the attributes associated to the allowed values.

This section defines the predicates restrictions, by directly mapping the UML classes into the OWL concepts restrictions (Kilian, et al., 2005), (Schreiber, 2005) (see Annex A for more details). In this description, it is analysed separately each concept and identified the restrictions of the existing predicates associated to the concept. The fulfilment of the identified restrictions is crucial to preserve the consistency of the ontology.

Operation The class "Operation" has several attributes as illustrated in figure. Some of them are relations with the classes, namely requiresProperty (with the class "*Property*"), requiresSetup (with the class "*Setup*"), *createsFunction* (with the class "*Function*"), hasPossibleResources (with the class "*Resource*"), usesMaterialFamily (with the class "*MaterialFamily*"), and comprisesOperation and hasOperationPrecedence (with itself). Additionally, it has DataType properties, such as duration, name, operationID and type.

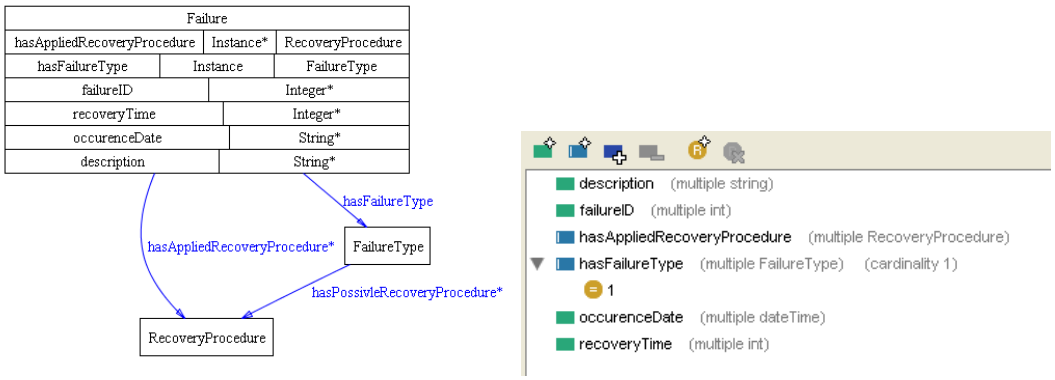


The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicates **createsFunction**, **requiresSetup** and **usesMaterialFamily** have the restriction minCardinality = 1, i.e. the cardinality of these relations is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

The predicates **requiresProperty**, **hasPossibleResources**, **comprisesOperation**, and **hasOperationPrecedence** don't present any restriction in terms of cardinality.

Failure The class "Failure" has several attributes as illustrated in figure. Some of them are relations with the classes, namely hasFailureType (with the class "*FailureType*") and hasAppliedRecoveryProcedure (with the class "*RecoveryProcedure*"). Additionally, it has DataType properties, such as failureID, occurrenceDate and recoveryTime.

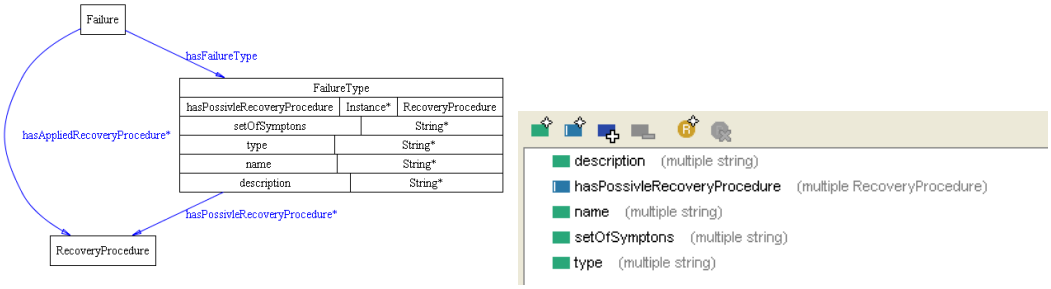


The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicate hasFailureType has the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

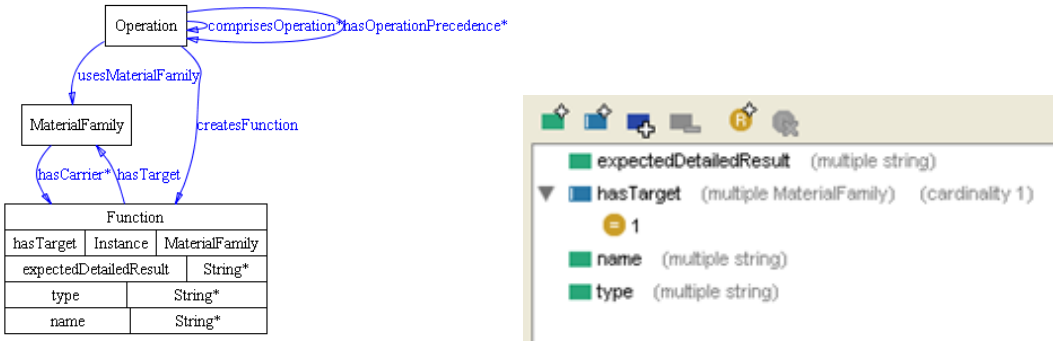
The predicate **hasAppliedRecoveryProcedure** don't present any restriction in terms of cardinality.

FailureType The class "FailureType" has several attributes as illustrated in figure. One is the relation hasPossibleRecoveryProcedures (with the class "*RecoveryProcedure*"), and others are DataType properties, such as name, description, setOfSymptoms and type.



The predicate has restrictions due to the association among the classes. In terms of cardinality, the predicate **hasPossibleRecoveryProcedures** don't present any restriction.

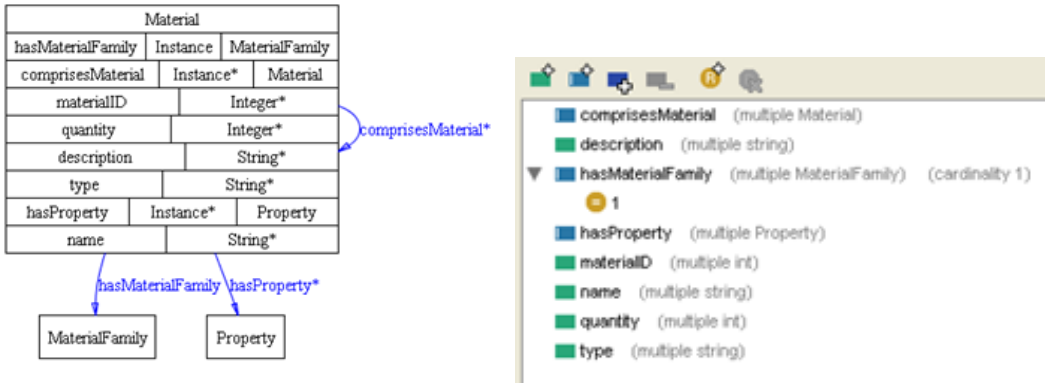
Function The class "Function" has several attributes as illustrated in figure. One is the relation hasTarget (with the class "*MaterialFamily*"), and others are DataType properties, such as name, expectedDetailedResult and type.



The defined relation has a specific restriction: in terms of cardinality, the cardinality of this relation is equal to 1, i.e. minCardinality = 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

Material The class "Material" has several attributes as illustrated in figure. Some of them are relations with the classes, namely hasMaterialFamily (with the class "*MaterialFamily*"), hasProperty (with the class "*Property*") and comprisesMaterial (with itself). Additionally, it has DataType properties, such as description, name, materialID, quantity and type.

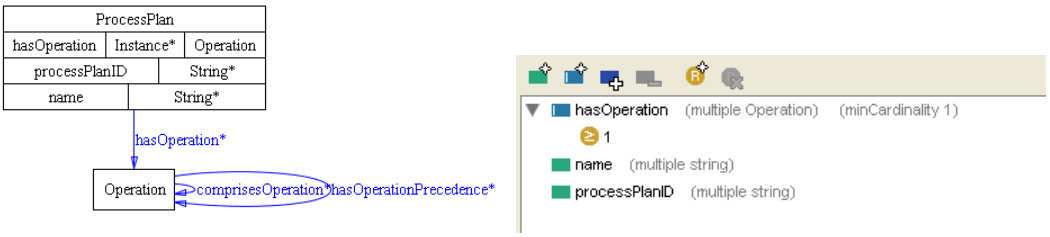


The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicate hasMaterialFamily has the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

The predicates **comprisesMaterial** and **hasProperty** don't present any restriction in terms of cardinality.

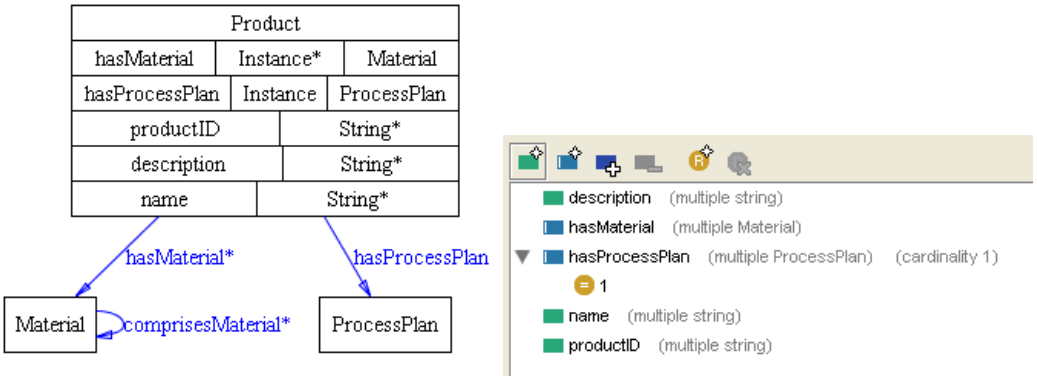
ProcessPlan The class "ProcessPlan" has several attributes as illustrated in figure. One is the relation hasOperation (with the class "*Operation*"), and others are DataType properties, such as processPlanID and name.



The defined relation is an aggregation and has a specific restriction: in terms of cardinality, the cardinality of this relation is more than 1, i.e. minCardinality ≥ 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| \geq N\right) \text{ the N is 1.}$$

Product The class "Product" has several attributes as illustrated in figure. Some of them are relations with the classes, namely hasMaterial (with the class "*MaterialFamily*") and hasProcessPlan (with the class "*ProcessPlan*"). Additionally, it has DataType properties, such as description, productID and name.



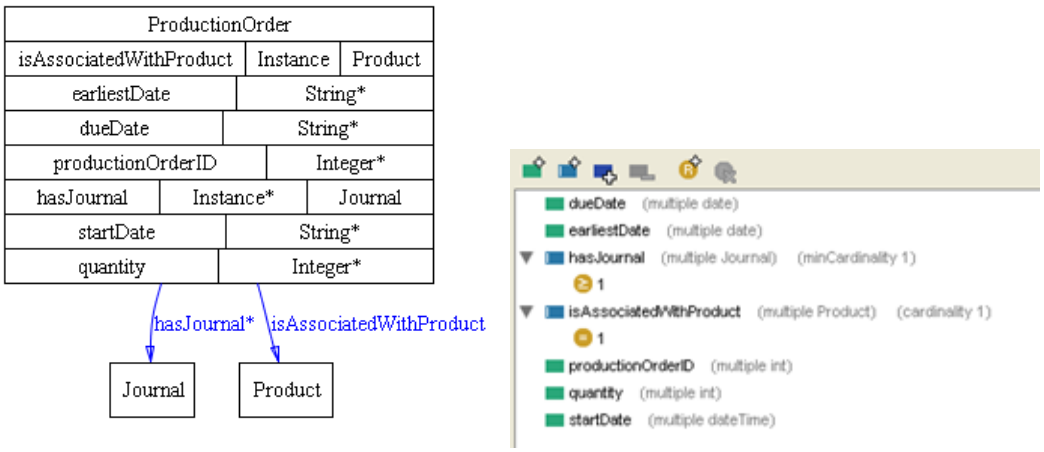
The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicate hasProcessPlan

has the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

The predicate hasMaterial doesn't present any restriction in terms of cardinality.

ProductionOrder The class "ProductionOrder" has several attributes as illustrated in figure. Some of them are relations with the classes, namely isAssociatedWithProduct (with the class "*Product*") and hasJournal (with the class "*Journal*"). Additionally, it has DataType properties, such as productionOrderID, quantity, startDate, earliestDate and dueDate.



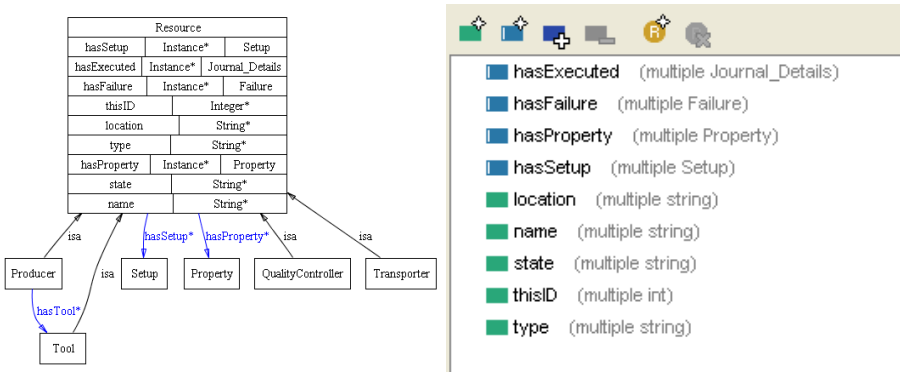
The defined relations have specific restrictions. The predicate isAssociatedtWithProduct is an association that has the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

The predicate hasJournal is a composition that has the restriction minCardinality ≥ 1, i.e. the cardinality of this relation is more than 1, or in a more formal manner,

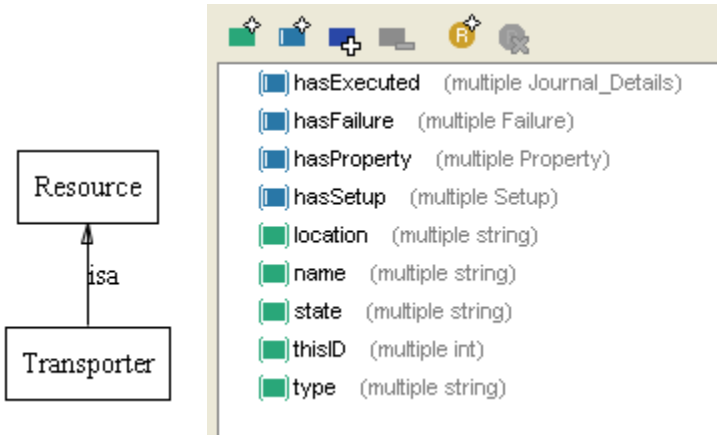
$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| \geq N\right) \text{ the N is 1.}$$

Resource The class "*Resource*" has several attributes as illustrated in figure. Some of them are relations with the classes, namely hasFailure (with the class "*Failure*"), hasProperty (with the class "*Property*") and hasSetup (with the class "*Setup*"). Additionally, it has DataType properties, such as name, thisID, type, state and location.

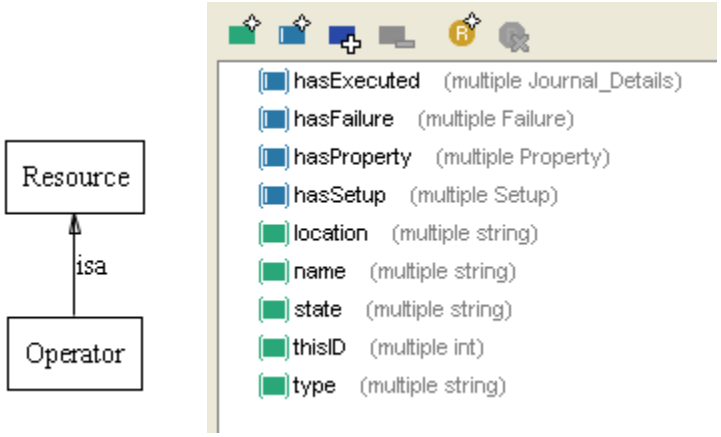


The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicates don't present any restriction in terms of cardinality. A special remark on the attribute thisID: Since the inherited classes will received the same kind of attributes of the Resource class, it does not make any sense to create an unique attribute for the identification of each one, so a generic label attribute is created to be derived lately by each inherited class.

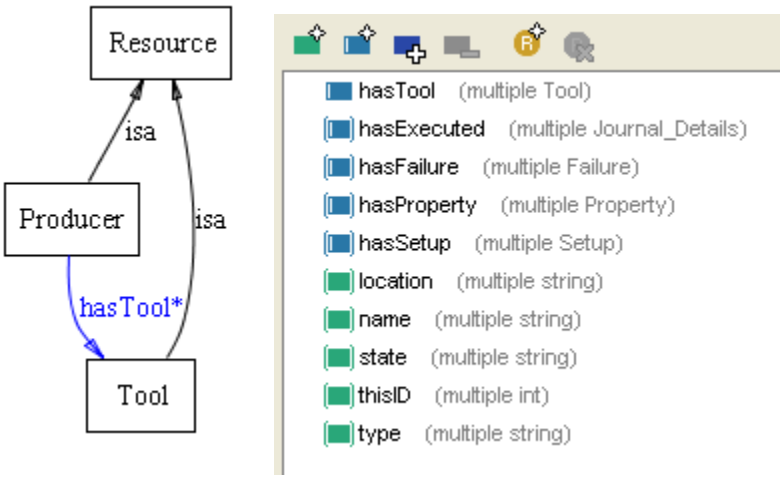
Transporter The class "*Transporter*" has several attributes as illustrated in figure, all of them are inherited from the class "*Resource*", since the class "*Transporter*" is a specialization of the class "*Resource*". In terms of restrictions, they are also inherited from the parent restrictions.



Operator The class "*Operator*" has several attributes as illustrated in figure, all of them are inherited from the class "*Resource*", since the class "*Operator*" is a specialization of the class "*Resource*". In terms of restrictions, they are also inherited from the parent restrictions.

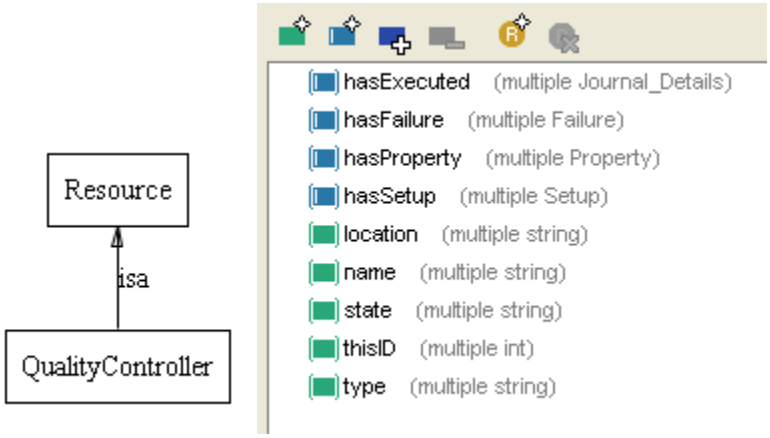


Producer The class "*Producer*" has several attributes as illustrated in figure, most of them are inherited from the class "*Resource*", since the class "*Producer*" is a specialization of the class "*Resource*". In terms of restrictions, they are also inherited from the parent restrictions.

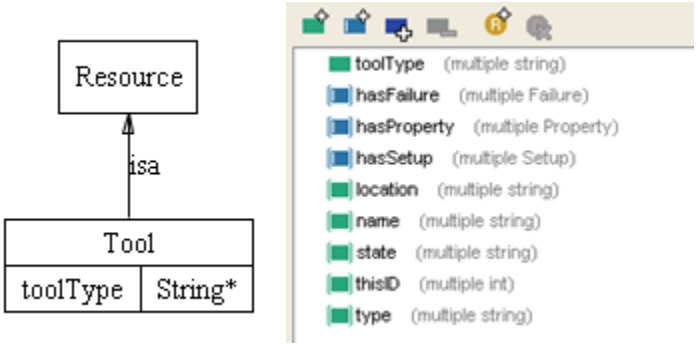


Besides the inherited attributes, this class has the relation hasTool (with the class "*Tool*"), that in an association between the two classes. In terms of cardinality, the predicate doesn't have any restriction.

QualityController The class "*QualityController*" has several attributes as illustrated in figure, all of them are inherited from the class "*Resource*", since the class "*QualityController*" is a specialization of the class "*Resource*". In terms of restrictions, they are also inherited from the parent restrictions.



Tool The class "*Tool*" has several attributes as illustrated in figure, most of them are inherited from the class "*Resource*", since the class *"Tool"* is a specialization of the class "*Resource*". In terms of restrictions, they are also inherited from the parent restrictions.



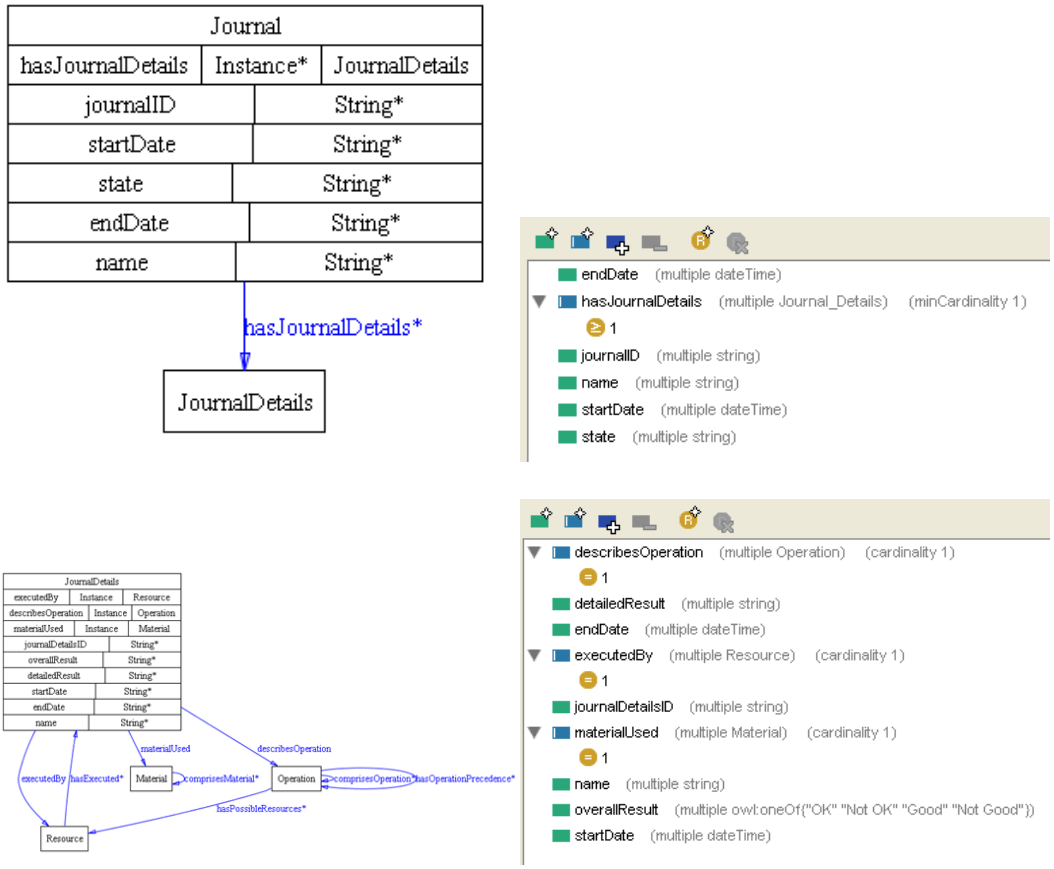
Besides the inherited attributes, this class has the attribute toolType as DataType properties.

Journal The class "*Journal*" has several attributes as illustrated in figure. One is the relation hasJournalDetails (with the class "*JournalDetails*"), and others are DataType properties, such as journalID, state, startDate and endDate.

The defined association relation is a composition and has a specific restriction: in terms of cardinality, the cardinality of this relation is more than 1, i.e. minCardinality ≥ 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| \geq N\right) \text{ the N is 1.}$$

JournalDetails The class "*JournalDetails*" has several attributes as illustrated in figure. Some of them are relations with the classes, namely describesOperation (with the class "*Operation*"), executedBy (with the class "*Resource*") and materialUsed (with the class "*Material*").



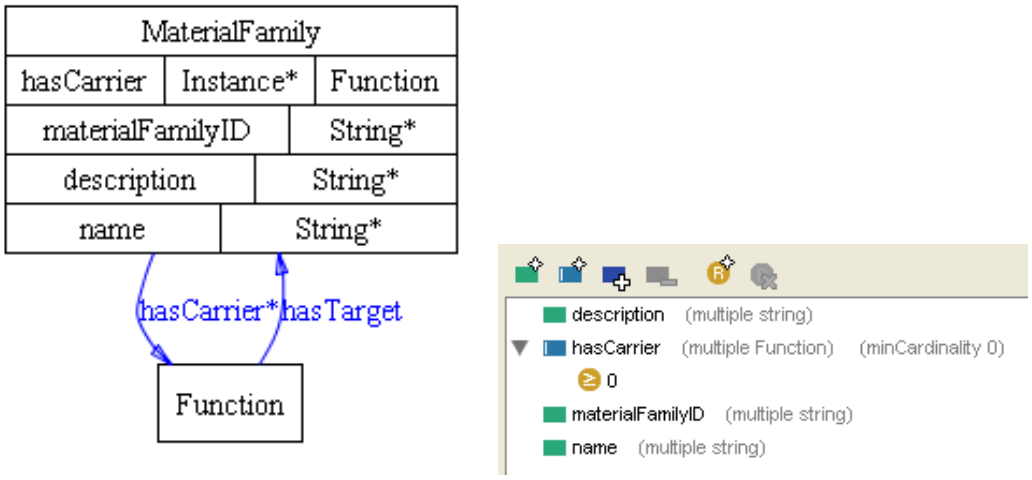
Additionally, it has DataType properties, such as journalDetailsID, name, overallResult, detailedResult, startDate and endDate.

The defined relations have specific restrictions. In terms of the type of connection, all of them are associations among the classes. In terms of cardinality, the predicates describesOperation, materialUsed and executedBy have the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

MaterialFamily The class "*MaterialFamily*" has several attributes as illustrated in figure. One is the relation hasCarrier (with the class "*Function*") and the others are DataType

properties, such as materialFamilyID and description.



The hasCarrier is an association and in terms of cardinality has the restriction minCardinality = 1, i.e. the cardinality of this relation is equal to 1, or in a more formal manner,

$$\forall x \left(A(x) \rightarrow |\left\{y|R\left(x,y\right)\right\}| = N\right) \text{ the N is 1.}$$

A.4 Validation

This section describes the manual validation performed by instantiation for a case study derived from a washing machine production line. The representation of the GRACE ontology classes, their relations and their own instances for this case study. In order to achieve a better understanding, the instantiation will be presented by analysing separately different parts of the ontology model, i.e. different fragments.

Figure A.3 illustrates two different instances of the class "*Product*", i.e. namely the product "_859201049010_0000" and "_859201049011_1111", representing two different product models that can be produced in the production line.

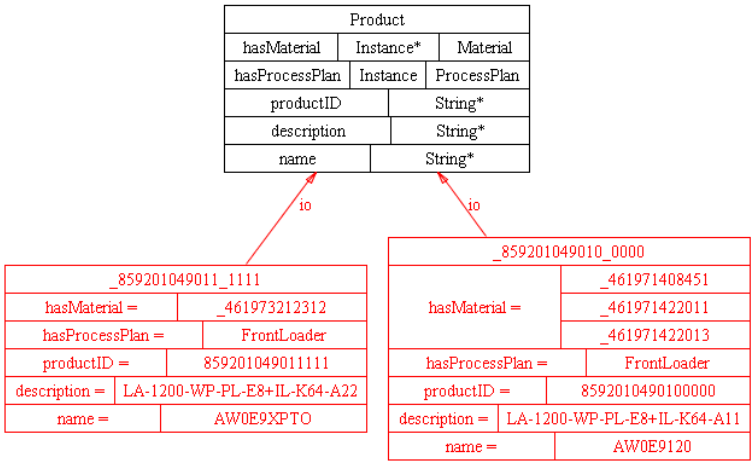


Figure A.3: *Representation of class "Product" and its instances.*

Note that the relation "io", represented between the class and the object, means "instance of". The two instances of the product class are filled with the real data in their attributes, e.g. in the case of the instance "_859201049010_0000", the DataType attributes name and description are respectively filled with "AW0E9120" and "LA-1200-WP-PL-E8+IL-K64-A11", and the ObjectProperty attribute hasProcessPlan is filled with the link to the "*ProcessPlan*" class "*FrontLoader*".

In a progressive manner, it is possible to analyse more parts of the ontology. Figure A.4 represents the several instances of the "*MaterialFamily*" class, namely "RearTub", "Hub", "ABearing", "BBearing", "ShaftSeal" and "CrossPiece". The relation hasMaterial between the "*Product*" and "*MaterialFamily*" classes is also defined for the different instances of the "*Product*" classes. After instantiating the different types of materials, the relationship between the classes was automatically reflected among the objects; e.g. the product "_859201049010_0000" has the following materials: "_461971408451", "_461971422013" and "_461971422011". This exercise is followed to the rest of the instances.

Figure A.4 shows the class "*Resource*" and the six instances considered in this model: "Seal_Insertion1", "Seal_Insertion2", "Bearing_Insertion1", "Bearing_Insertion2", "Marriage1" and "Marriage2". Each one of these instances is filled with the details about its characteristics. Figure A.5 illustrates the classes and their instances.

Figure A.5 illustrates the validation of the fragment of the ontology comprising the "*Pro-*

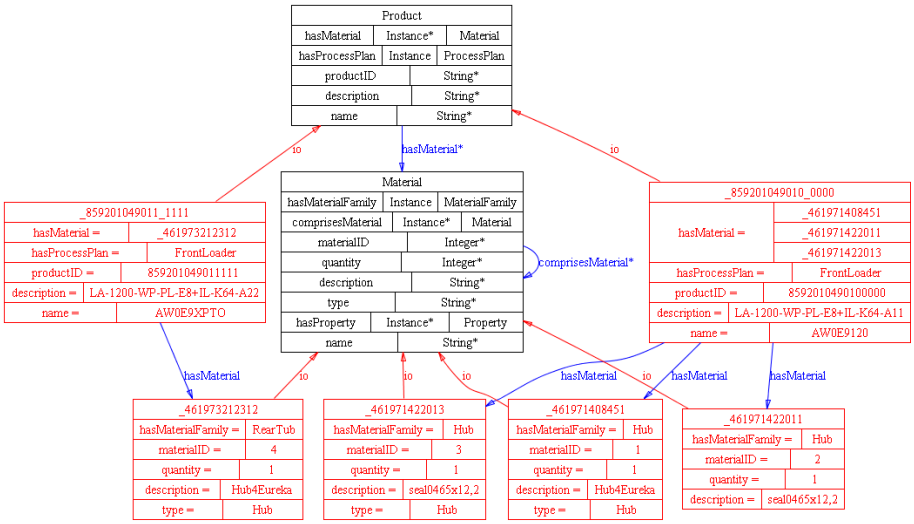


Figure A.4: *Representation of the "Product" and "Material" classes and their instances.*

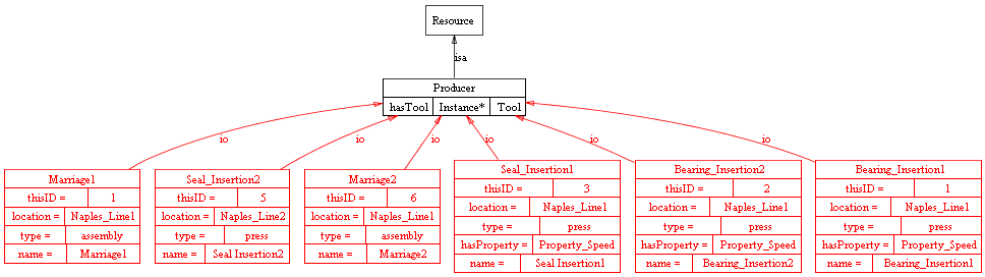


Figure A.5: *Representation of the "Resource" class and its instances.*

cessPlan", "*Operation*" and "*Resource*" concepts. Here, it is possible to verify that the process plan "FrontLoader", that defines the process to execute the product "_859201049010_0000", comprises the execution of three operations:

- "BearingInsertion-Program1", which uses components from the "ABearing", "BBearing" and "RearTub" material families.
- "SealInsertion-Program1", which should only be executed after the execution of the operation "BearingInsertion-Program1", and uses components from the "RearTub" and "ShaftSeal" material families.
- "Marriage-RearTub-Drum-Program1", which should only be executed after the execu-

tion of the operation "SealInsertion-Program1", and uses components from the "ABearing", "BBearing" and "CrossPiece" material families.

Figure A.6 illustrates the example with more detail:

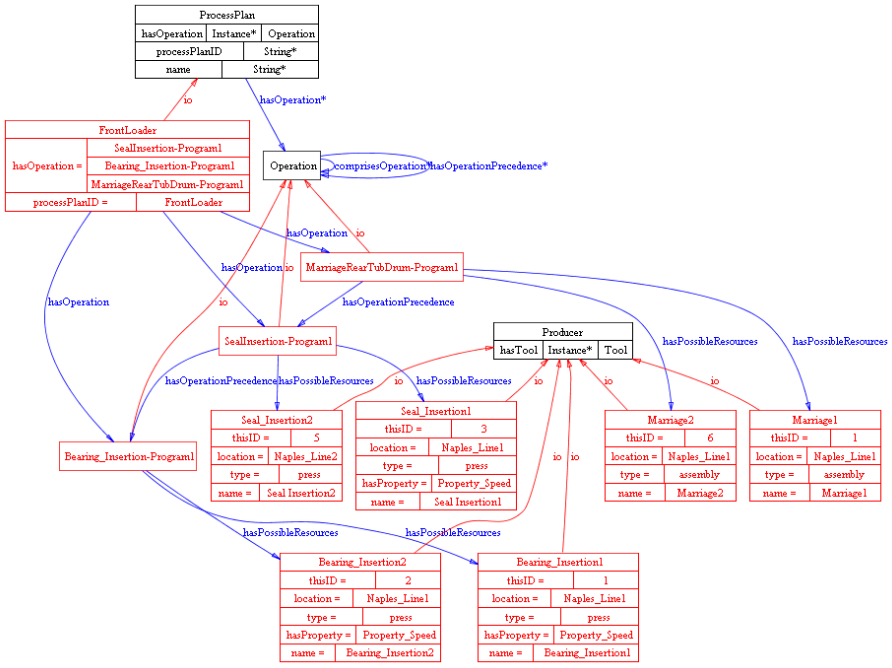


Figure A.6: *Representation of the "ProcessPlan", "Operation" and "Resource" classes and their instances.*

Also in this fragment, it is possible to verify the indication of the possible resources that can execute each operation. In this way:

- The operation "BearingInsertion-Program1" can be executed by the resources "Bearing_Insertion1" and "Bearing_Insertion2".
- The operation "SealInsertion-Program1" can be executed by the resources "Seal_Insertion1" and "Seal_Insertion2".
- The operation "Marriage-RearTub-Drum-Program1" can be executed by the resources "Marriage1" and "Marriage2".

Another important fragment to be analysed, is the static data model related to the "Material-Family", "Operation" and "Function" model, illustrated in Figure A.7, which is an innovative feature of the GRACE ontology.

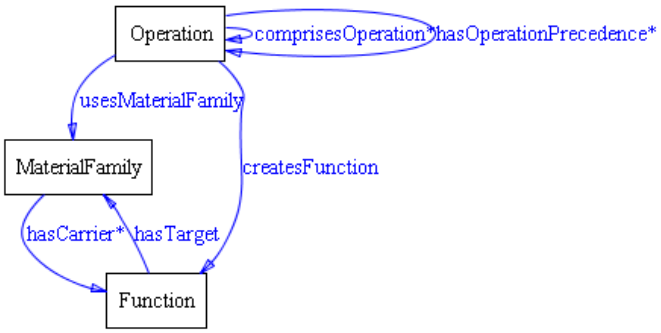


Figure A.7: *MaterialFamily-Operation-Function model.*

The previous figure illustrates the instantiation for the MaterialFamily-Operation-Function model. Here, it is possible to verify that the several operations described in the ontology model will create, each one, a function.

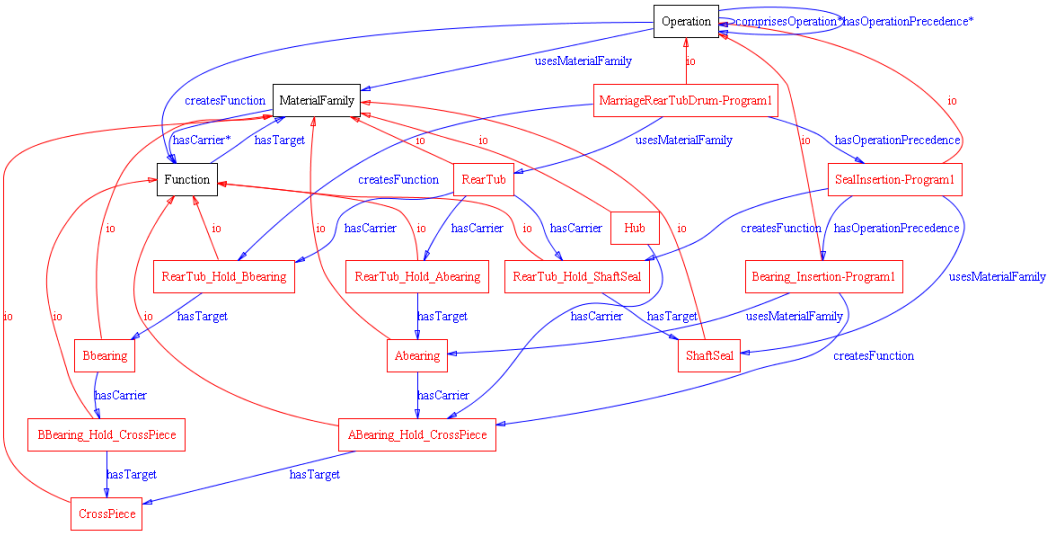


Figure A.8: *Representation of the "MaterialFamily", "Operation" and "Function" classes and their instances.*

Examples of the functions created are the function "BBearing_Hold_CrossPiece", "ABearing_Hold_CrossPiece", the funciton "RearTub_Hold_ABearing", "RearTub_Hold_ BBearing" and "RearTub_Hold_ ShaftSeal".

The relations between the class "*Function*" and the class "*MaterialFamily*", i.e. hasCarrier and hasTarget, allow indicating which components are involved in the operation that creates the function, defined through the relation between the "*Function*" and "*Operation*" classes. For example, the function "ABearing_Hold_CrossPiece" is completely defined by the following relations:

- hasCarrier: "ABearing"
- hasTarget: "CrossPiece"
- createsFunction: "Marriage-RearTub-Drum-Program1"

Another perspective of the ontology is related to the classes that describe the dynamic production data related to the execution of production orders in the production line, i.e. the classes "*ProductionOrder*", "*Journal*" and "*JournalDetails*", as illustrates the Figure A.9.

Here, it is considered a production order to produce a batch of 2 items of the product "_859201049010_0000". The order leads to the production of the two machines described by the instances "Journal_411142011153" and "Journal_411142011154" from the "Journal" class. Since the production of this product model requires the execution of three operations, as described in the process plan, each one of the instances "Journal_411142011153" and "Journal_411142011154" has three instances of the "JournalDetails" class, related to the description of the execution of each operation. For example, for the machine produced in the production line and described with "Journal_411142011153", the details are:

- "Journal_Details1": the operation "BearingInsertion-Program1" was performed by the resource "Bearing_Insertion1" with an overall result of OK.
- "Journal_Details2": the operation "SealInsertion-Program1" was performed by the resource "Seal_Insertion1" with an overall result of OK.
- "Journal_Details3": the operation "Marriage-RearTub-Drum-Program1" was performed by the resource "Marriage1" with an overall result of OK.

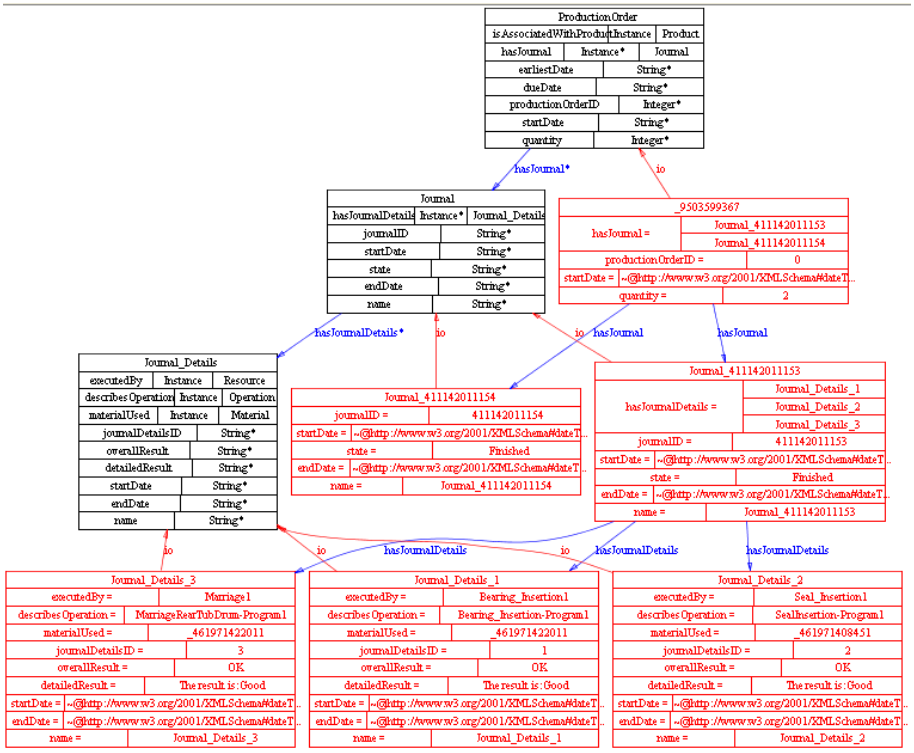


Figure A.9: *Representation of the "ProductionOrder", "Journal" and "JournalDetails" classes and their instances.*

The manual validation of the schema ontology allowed a better understanding of the considered domain and the correction of some misunderstanding issues in the design of the ontological concepts, predicates, attributes and restrictions.

Other tools and methods may also be used for evaluating the functionality of the ontology, e.g. OntoMetric [53] and OntoClean [33] that are used to detect both formal and semantic inconsistencies. In this work, the validation was performed using the capability provided by the Protégé framework, as previously described. At this stage, the designed ontology is ready to be used, i.e. implemented to be integrated in the multi-agent system specified in the [60].

Appendix B

Frameworks to Develop Agent-based Solutions

JADE is a Java-based architecture that uses the Java Remote Method Invocation (RMI) to support the creation of distributed Java technology-based to Java applications. Each agent is implemented with Java "threads" and associated with a container.

JADE aims to simplify the development of multi-agent systems by providing a set of services and agents in compliance with the FIPA specifications, e.g. naming service and yellow-page service, message transport and parsing service, and a library of FIPA interaction protocols ready to be used [7]. Note that in the essence, the agents developed using the JADE platform are Java Threads, which makes the debugging of multi-threading very difficult; consequently, some tools have been developed to simplify the development of agent-based solutions, being every single tool provided by JADE packaged as an agent itself.

B.1 Comparison between Agent Development Platforms

After several tools have been studied, only a few were chosen. These platforms share between them the fact of being FIPA compliance. Thus the final choice will be a tool that meets the FIPA's standards.

FIPA has several platforms the most important are: FIPA-OS, Grasshopper, JACK In-

telligent Agents, ZEUS [64], April Agent Platform, JADE [7], and Agent Development kit. In Figure B.1 a comparison between these platforms is shown, taking into account several examples.

Platform	Licence	Architecture	FIPA compliance	Light Weighted	Still Maintained	Being Developed
JADE	Freeware	Reactive	✓	✓	✓	✓
FIPA-OS		Reactive	✓	✓	×	×
JACK	Commercial	BDI		✓	✓	✓
April				×	×	×
Grassjopper				×	×	×
ZEUS		Reactive		×	×	×

Figure B.1: *Comparison of several Agent Platforms according to the needs.*

For further analyses about the comparisons between platforms, the following article can be consulted [51] and [81] for Java based platforms. Taking into account the values in this table, it can be verified that JADE platform is a platform that brings together a greater number of points in its own favour, and has a Freeware licence. The API documentation is distributed with JADE, also the source code is available on JADE website along with several plugins.

B.2 JADE tools

JADE multi-agent system application is composed of the ACC, AMS and DF agents, and by an RMI registry (that is used by the JADE for intra-platform communication), as illustrated in Figure B.2.

The AMS, illustrated in Figure, which provides white pages and agent life cycle management services (controlling the access to the platform, authentication, and registration), maintaining a directory of agent identifiers and states.

The communication among the agents is performed through message passing, where FIPA-ACL (Agent Communication Language) is the agent communication language to represent messages. JADE provides the FIPA SL (Semantic Language) content language and the agent management ontology, as well as the support for user-defined content languages and

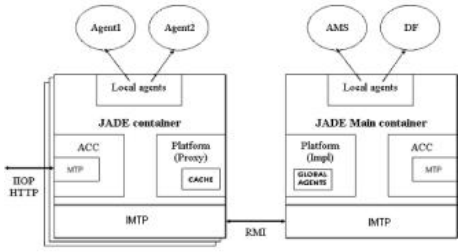


Figure B.2: *Structure of the Agent Management System (AMS).*

ontologies that can be implemented, registered with agents, and automatically used by the framework.

The Remote Management Agent (RMA) provides a Graphical User Interface (GUI) for the remote management of the platform, allowing monitoring and controlling the status of agents, for example to stop and re-start agents, Figure B.3. The RMA allow a fully control of an agent life cycle from a remote host. When the Jade platform is started, a default container is created, which holds the RMA itself, the DF, and AMS.

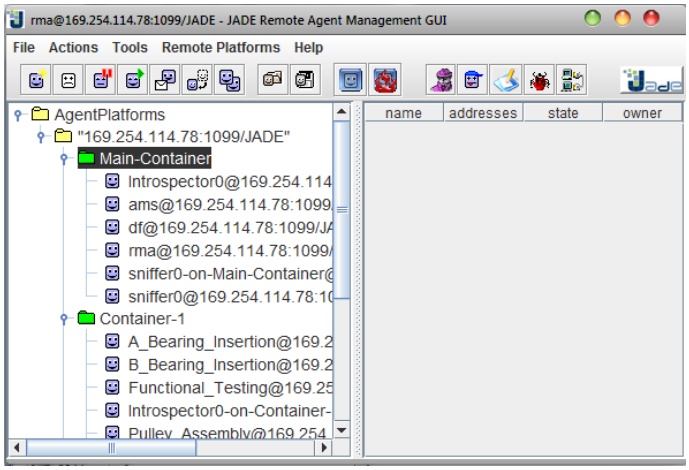


Figure B.3: *Remote Management Agent.*

The RMA agent provides a set of graphical tools (packaged as agents) to monitor the state of the agents and to support the debugging phase, usually quite complex in distributed systems, such as the Dummy, Sniffer and Introspector agents.

In distributed systems it is important to have a service of yellow pages, where agents

register their services and skills to be found by other agents. In the JADE platform, this concept is named as Direct Facilitator (DF) following the FIPA specifications. This yellow pages services allow to see the details of agents registration, deregister the agents, modify some descriptions, or as the greatest utility of the yellow pages, look for a service that is performed by another agent. Figure B.4 illustrates the screenshot of the DF.

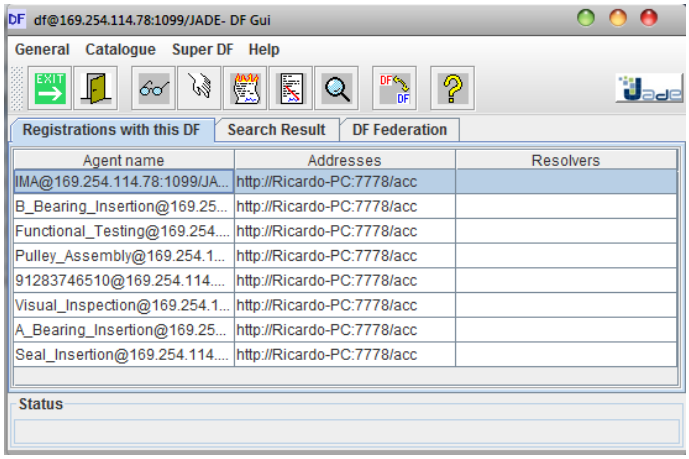


Figure B.4: *Graphical User Interface of the Director Facilitator.*

When the complexity of the multi-agent system increases, it is very useful to use a tool to check the exchanged messages between the agents. The Sniffer Agent, illustrated in Figure B.5, is a debugging tool that allows tracking messages exchanged in a JADE agent platform using a notation similar to Unified Modelling Language (UML) sequence diagrams. It can be analysed the type of message, the FIPA protocol, the ontology language and its contents.

This tool is very powerful, because it allows seeing and controlling a bunch of Jade's tools. It is possible to check the messages that are shared on the platform, the incoming and the outgoing messages (just like with the sniffer tool).

The Introspector Agent, illustrated in Figure B.6, allows monitoring and controlling the life-cycle of a running agent, its exchanged ACL messages (incoming and the outgoing messages) and the behaviours in execution (allowing to execute them step-by-step).

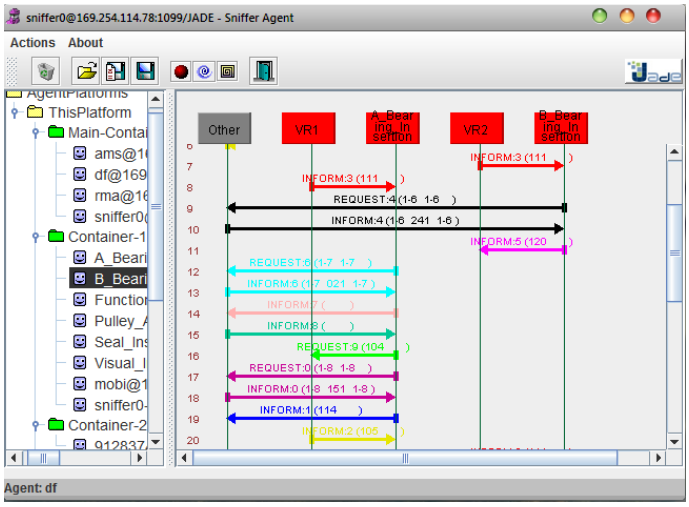


Figure B.5: *Sniffer agent.*

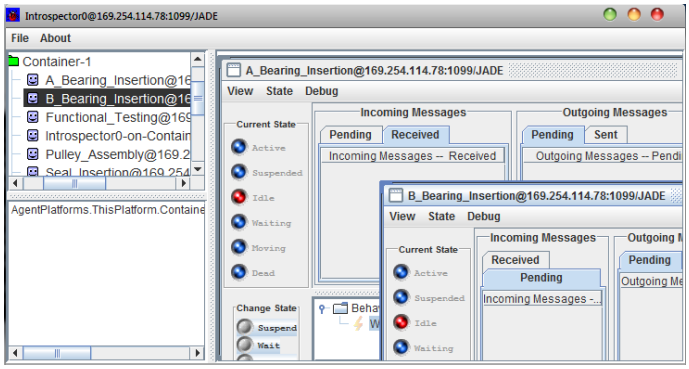


Figure B.6: *Graphical User Interface of the Instrospector Agent .*

B.3 Jade Basics Services

For the creation of a Jade agent, it is required to declare it as a subclass of the class *Agent*, by simply extending the class *jade.core.Agent*. The beginning of the agent is given firstly by the *setup()* method, regardless of the agent.

Each agent performs an action that action, and is represented by a behaviour. The JADE platform offers several possibilities in terms of conducts. Created a new class is required to inherit the functionality of the class *jade.core.Behaviour*. The follow piece of code illustrates these two cases described.

```
import jade.core.Agent;
import jade.core.behaviours.Behaviour;
public class MyAgent extends Agent{
  System.out.println("Hello world!");
  addBehaviour (new MyBehaviour(this));
}
```

The execution cycle of the agent, regardless of the kind of behaviour that is occurring, becomes quite simple. In Figure B.7 is an example represented:

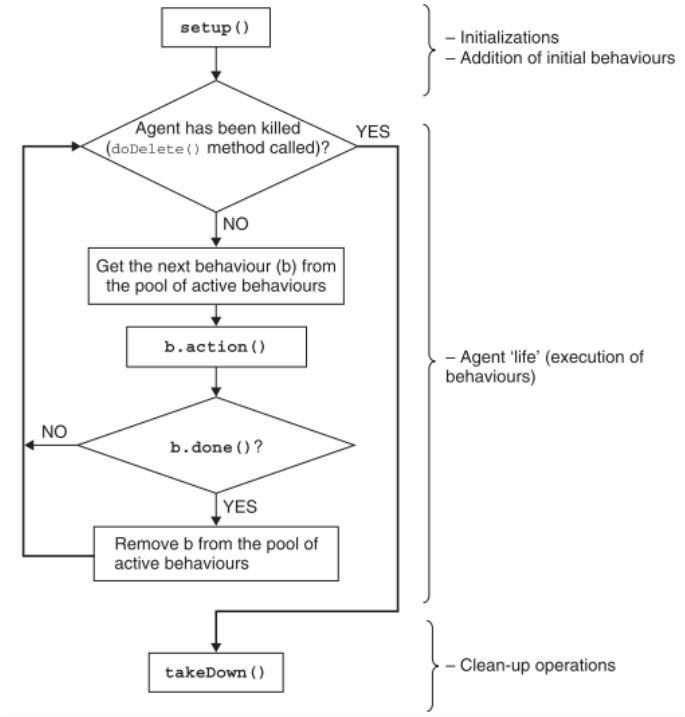


Figure B.7: *Agent execution cycle [7] .*

Analysing the anatomy of the agent's cycle are functions that deserve special attention, *setup()*, *action()*, *done()*, *takeDown()*.

- *setup()*, represents the agent start up.
- *action()*, implements the code, which refers the behaviour to be executed.

- *done()*, tests the final behaviour, returning a Boolean, if is false will continue to the *takeDown()* method, otherwise returns to the *action()* method.
- *takeDown()*, it is where should be declared the last operations that the agent will perform.

Jade also provides possibilities to choose behaviours already pre-defined, internally. These kinds of behaviours have the logic of the previous methods already implemented. Table B.1 shows the range of behaviour that Jade provides.

Table B.1: *Behaviours provided by JADE platform.*

Behaviour	Description
One-Shot Behaviour	Performing once instantaneously
Cyclic Behaviour (CyclicBehaviour)	Behaviours that never ends, (because the method done() returns always false)
Temp Behaviour (WakerBehaviour, TickerBehaviour)	Are behaviours that include a temporal relationship in their execution
Compose Behaviour (SequencialBehaviour, ParallelBehaviour, FSMBehaviour)	Are specific behaviours: sequential, parallel and state machine

The developer must study the potential of these behaviours before implementing by himself a behaviour that has the same objective.