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Unambiguous requirements in Functional Safety and ISO 26262: dream or reality?

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Abstract

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Functional Safety is becoming an increasingly important concern for in-vehicle E/E systems. In 2011 a new international standard, ISO 26262 "Functional safety - Road vehicles" was published, in which requirements play an important role.

In this thesis, the advantages and disadvantages of different levels of formality in requirement notations are discussed. It is found that the higher the level of formality, the less ambiguous will the requirements specified in the notation be. Furthermore, it is found that ISO 26262 mandate that all requirements must be unambiguous and at the same time preferably written in natural language. This is considered inconsistent since natural language is inherently ambiguous.

A case study is performed where a domain ontology and a constrained natural language (CNL) in the form of boilerplates are used to write and analyse requirements. An important conclusion is that getting requirements right is a hard task, but that the use of ontologies both can decrease ambiguity and establish a shared vocabulary among stakeholders.

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Contents

About Scania CV

For the benefit of the reader, a brief introduction about Scania CV is provided in the below quote, which is copied verbatim from the corporate website:

> Scania's objective is to deliver optimised heavy trucks and buses, engines and services, provide the best total operating economy for our customers, and thereby be the leading company in our industry. The foundation is our core values, our focus on methods and the dedicated people of Scania.
>
> Scania operates in about 100 countries and has more than 35,500 employees. Of these, around 15,000 work with sales and services in Scania's own subsidiaries around the world. About 12,300 people work at production units in seven countries and delivery centres in six emerging markets. Research and development operations are concentrated in Södertälje, Sweden, and employ some 2,900 people. Scania's Head Office is located in Södertälje, the workplace of most of the 5,300 people who perform administrative and other tasks. Scania's corporate purchasing department in Södertälje is supplemented by local procurement offices in Poland, the Czech Republic, the United States, China and Russia.
>
> Scania's identity is shaped by its customers and products – vehicles, services and financing – and by the people in the company, their values and working methods.
>
> Three core values – Customer first, Respect for the individual and Quality – tie the company together and form the basis of Scania's culture, leadership and business success.
>
> Scania's modular product system, with a limited number of main components, allows a high degree of customisation, while keeping down the cost of product development and production as well as parts management. Tailoring each vehicle to specific transport needs gives the customer better overall operating economy.
>
> Scania should contribute to sustainable economic growth, for the company, our customers and society at large. As an industry leader in sustainable efforts, Scania works together with governments, customers and organisations to provide reliable energy-efficient products and solutions that increase customer efficiency and contribute to a more sustainable society. [46]

Part I:
Background

1. Introduction

The advances of the last decade in E/E (Electrical/Electronic) systems have made it possible to build increasingly advanced in-vehicle systems. The number of such systems in each individual vehicle has also increased, as has the complexity within each specific system.

This trend is likely to continue, especially in the field of ADAS (Advanced Driver Assistance Systems). As the E/E systems also becomes increasingly responsible for maintaining the safety of the vehicle and its environment, the correctness of the systems becomes imperative. This in turn puts higher demands on the development processes.

In November 2011, ISO 26262 "*Road Vehicles – Functional Safety*" [31] was published as a formal ISO standard, but draft versions have been available to interested parties for some time prior to the publication. ISO 26262 is a domain specific realisation of the IEC 61508 standard, which covers functional safety in E/E systems.

ISO 26262 is applicable only for vehicles with a weight less than 3500 kg, but it is expected that heavier road vehicles will be encompassed after the first revision of the standard. Scania CV, which has commissioned this thesis, is interested in knowing what impact the standard would have on their work processes if it were to be adhered to during systems development.

During spring 2011, two students from Mälardalen University College performed a joint master thesis where they did a gap analysis [35] which compared the development processes at Scania with a draft of ISO 26262. The analysis identified some areas in need of improvement, especially in regard to system requirements.

In order to gain additional insight into the standard as well as improving the knowledge about system requirements, this thesis was commissioned.

As the title of this thesis implies, there will be a focus on notations and ambiguity. In particular, the high-level objective is to reduce or, if possible, even altogether *remove* ambiguity in requirement specifications.

The focus on ambiguity is motivated since a lot of literature highlights ambiguous requirements as a common problem, and also because ISO 26262 state that safety requirements shall be "unambiguous and comprehensible" [31].

This leads to the main question of this thesis: *is it possible to achieve unambiguous requirements in a context of functional safety and ISO 26262?*, which is further concretised into three objectives:

I. Describe how different levels of formality in the notations used to represent the requirements affects ambiguity, as well as other relevant considerations pertaining to each covered notation.

II. Describe the requirements from ISO 26262 regarding different notations.

III. Investigate, in a long term perspective, suitable techniques for reducing ambiguity and if possible, achieving automated requirements analysis.

Some limitations in scope are necessary. First, focus will be on "higher level requirements", i.e., requirements at a high level of abstraction. Those are usually associated with end user and other stakeholder needs. Secondly, there will be no in-depth comparisons between methods and techniques; instead, a "proof of concept" perspective will be used.

1.1 Disposition

This thesis is organised in six parts.

- Part (I) contains background information.
- Part (II) contains related work and describes the method used to arrive at the results.
- Part (III) contains the major portion of the theoretical material.
- Part (IV) contains a case study where a research tool is evaluated within the context of a Scania system.
- Part (V) contains a discussion about the results from the previous parts.
- Part (VI) concludes the thesis and ultimately provide suggestions for future work.

1.2 Style

Normal text is using a standard font. Emphasis is used to highlight *important* words or sentences. Bold font *is not* used in normal text, but appears in quotations where the original source used it. Quotes longer than a sentence will appear as separate indented paragraphs, while shorter quotes appears within "citation" marks. Frequently occurring acronyms are marked like THIS.

In the electronic version of this thesis, important concepts and acronyms are hyperlinked to their respective definition in the Glossary or Acronym list.

ISO 26262 is divided into Parts, each part is divided into Clauses, and each Clause contains a number of Paragraphs. For example, "ISO 26262-8 Clause 6" refers to Part 8, Clause 6. Paragraphs in ISO 26262 are hierarchically numbered starting from the Clause number. This means that "Paragraph 6.4.4.2" can exist in more than one Part.

The reader should be aware of the dual nature of the word "requirement". It is mainly used for describing a system or software requirement which is what this thesis mostly is about. However, it is also used in the sense of something prescribed or mandated by ISO 26262 or other normative sources. An attempt has been made to use other words for the latter case, but this has not always been possible.

2. Key concepts

In this chapter, a number of important concepts will be defined and explained. Although ISO 26262 is a key concept, a more thorough introduction of the standard is postponed until the next chapter.

When the terms below are used in the following chapters, it is the definitions herein that have precedence unless explicitly stated otherwise.

2.1 Requirements

In general terms, a requirement can for example be "something that is wanted or needed" or "something called for or demanded" [23].

In Software or Requirements Engineering, the former correspond closer to *goals*, while the latter is more aligned with the normal use of the word *requirement*.

However, a goal is also a type of requirement. The difference is the level where it is defined: a goal is a more general desire or want that the system should somehow fulfill - it may therefore be rather vague. A requirement, on the other hand is more succinct and specify something the system must be able to do.

There are also different types of requirements, but a discussion on this topic is outside the scope of this thesis. The interested reader may refer to books like *Writing Better Requirements* by Alexander and Stevens [3] or *Requirements Engineering* by Hull et al. [27].

Finally, one special type of requirement that not always is labelled as such, is an *assumption*. In this thesis, it is given the meaning of an explicit requirement on an external system.

2.2 Stakeholder

A *stakeholder* is a person or organisation with an interest in the outcome of the project or system. Exactly which parties that should be included in the term varies. For example, some consider the developers and testers to be stakeholders while others do not.

In this thesis, which is written with a Scania perspective, and also focusing on the top-level requirements, the following roles will be considered stakeholders unless stated otherwise:

- the function owner at Scania,
- the driver of the vehicle,
- the owner of the vehicle,
- the After Market department which is responsible for service manuals and the Driver's Manual, and
- the mechanics who will perform service.

2.3 Software, System and Requirements Engineering

The term Software Engineering became popular after a 1968 NATO conference about what was perceived as the "Software Crisis" [45]. Since that, it has evolved into a research field of its own. Software Engineering is about methods and processes for building software systems in a predictable way that ensures the quality of the product.

Systems Engineering predates Software Engineering, at least dating back to Bell Laboratories in the 1940s [30]. According to The International Council on Systems Engineering (INCOSE),

> Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. [29]

The difference is that Systems Engineering has a broader perspective than a piece of software in isolation, or even a software system where end users are considered part of the system.

Requirements Engineering is the field of gathering, specifying and managing requirements. While it is a key activity in both Systems and Software Engineering, it seems to be mostly associated with the latter.

2.4 Syntax and semantics

The following definitions are taken from the *Handbook of Practical Logic and Automated Reasoning*, and seems to be in line with other more implicit descriptions:

> The *syntax* of a language is a system of grammar laying out rules about how to produce or recognize grammatical phrases or sentences. [. . .]
>
> The *semantics* of a particular word , symbol, sign or phrase is simply its meaning. More broadly, the semantics of a language is a systematic way of ascribing such meanings to all the (grammatically) expressions in the language. [26]

2.5 Natural language

A natural language is a language that is used by native speakers of that language. Natural languages, as any other languages, have both syntax and semantics. In the book *Syntactic Structures*, Chomsky [15] explores, among other things, the challenges of separating grammatical sentences from ungrammatical ones. But even though a sentence is grammatical, it can still be nonsensical. Chomsky [15] presents the following example:

> (1) Colorless green ideas sleep furiously.
> (2) Furiously sleep ideas green colorless.

Both (1) and (2) above are nonsensical, but (1) is nevertheless grammatical.

It is also interesting to note that the number of sentences that are used by a native speaker is far less than the number of grammatically and semantically acceptable sentences [43].

This thesis will use a broad definition of natural language; any sentence which is sufficiently grammatically and semantically correct for native speaker is accepted as part of the language.

Furthermore, in this thesis natural languages are considered to lack *authorative rule sets* for determining grammatically and semantically correctness. This is motivated because natural languages tend to be constantly evolving, and also because a certain phrase can be interpreted differently depending on cultural factors such as age or profession.

2.6 Ambiguity

Ambiguity is the central theme in this thesis. A requirement is ambiguous if there are more than one possible interpretation of it.

For example, the following requirement is ambiguous:

> The system should automatically close the sluice if an emergency flood is detected.

The word "should" gives the designer the option to avoid implementing the requirement for whatever reason that seems appropriate to them, but from context one could assume that the author of the requirement meant "shall". However, it is never a good situation when people have to second-guess the intentions of the author.

The sample requirement has some other deficiencies as well, but the above is sufficient for the purpose of demonstrating ambiguity.

2.7 Formal methods

By using formal methods, it is possible to prove certain properties of the system and that a piece of software conforms to the specification. If there also exist a formal description of the environment the system will operate in, it is possible to prove that the system fulfils (e.g.) the desired safety properties in the environment. However, creating a formal description of the entire environment a truck operates in may be quite hard. Nevertheless, there are many more benefits with formal methods and these are covered in more detail in latter chapters.

In a survey from 2009 about the current usage of formal methods in industry, Woodcock et al. define formal methods to be:

> [. . .] mathematical techniques, often supported by tools, for developing software and hardware systems. Mathematical rigor enables users to analyze and verify these models at any part of the program life-cycle [. . .] [59]

In the articles *Seven myths of formal methods* by Hall [25] and *Seven more myths of formal methods* by Bowen and Hinchey [8], common misconceptions about formal methods are dicussed. Bowen and Hinchey also present *Ten commandments of formal methods* [9] as well as a "ten years later" follow-up [10] on the original paper. Both contains recommendations on how and when formal methods should be deployed.

A brief review of a number of formal methods, from an industrial perspective, can be found in the CESAR Project (see Chapter 4) report titled *Survey Report on Modeling Languages, Components Technologies and Validation Technologies for Real-Time Safety Critical Systems* [13].

Figure 2.1 contains a sample specification in the *B* notation. The specification describes a student council with members and a president, and is taken from the book *Specification of Software Systems* by Alagar and Periyasamy [2], which cover several different formal notations.

More in-depth material about specific methods is available in books like *Software Specification Methods* by Frappier and Habrias [21], *Modeling in Event-B* by Abrial [1], and *Constructing Correct Software* by Cooke [17].

```
MACHINE
  $StudentCouncil(limit)$

CONSTRAINTS
  $limit \in \mathcal{N}_1$

SETS
  $STUDENT$

VARIABLES
  $council, president$

INVARIANT
  $council \in \mathcal{P}(STUDENT) \wedge \textbf{card}(council) \leq \text{limit} \wedge$
  $president \in \text{STUDENT} \wedge$
  $(council \neq \phi \Rightarrow president \in council)$

INITIALIZATION
  $council := \phi \mid\mid$
  $president :\in STUDENT$

OPERATIONS
  AddStudent$(nn) =$
    PRE
      $nn \in STUDENT \wedge nn \notin council \wedge \textbf{card}(council) < limit$
    THEN
      IF $council = \phi$ THEN
        $president := nn$
      END $\mid\mid$
    $council := council \cup \{nn\}$
  END;
[...]
```

Figure 2.1. Example of the *B* notatation taken from the book *Specification of Software Systems* [2]. The example shows a specification of a student council. Elements from the set of students can be members of the council. If the council has any members, the president must be one of them. Double bars in B does not mean "logical or"; instead it means that the statements on both sides are executed in parallel, i.e. at the same time. The symbol $\mathcal{N}_1$ denotes integers greater than zero.

3. Functional Safety and ISO 26262

ISO 26262 is a standard about functional safety, which by ISO 26262 is defined as the "absence of unreasonable risk due to hazards caused by malfunctioning behaviour of E/E systems" [31]. A deeper discussion will not be provided, but ultimately, "unreasonable" boils down to the probability that someone dies due to an hazard caused by an E/E system.

ISO 26262 is a domain specific realisation of the more general purpose standard IEC 61508, which is sometimes informally referred to as "The mother of all [functional] safety standards". There are also realisations for other industries such as aviation, railway and heavy machinery.

One important difference between ISO 26262 and IEC 61508 is that the latter is written for mass-production of electronic components, while ISO 26262 is concerned about the safety in complete vehicles.

For mass-produced electronic hardware products, it is possible to produce statistics such as mean time to failure, which then can be used to calculate probabilities in a safety situation. Unfortunately, this is much harder to do for a software system; it can be proved to be *unsafe*, but not the other way around.

Therefore, the importance of being able to make a strong case that a particular system indeed is safe increases. One way to do so is to have an established process which follows good development practices, and the approach taken by ISO 26262 is to provide a set of requirements regarding the entire development lifecycle. This set of requirements is on a fairly detailed level; the entire standard consists of approximately 400 pages.

Overall, different aspects relating to requirements are a large part of the standard. Below is a brief explanation on how the standard makes use of requirements. Note that this is only a very small part, and that there are lots of other aspects such as testing and verification.

When a system is developed in accordance with the standard, the first thing that is needed is an *item definition*. This definition must, among other things, contain a description of the *item*, assumptions on external system dependencies and a preliminary architecture. Requirements or goals that are not safety-related will also be part of the definition.

It is important to note that an *item* is not the entire vehicle. The size of an *item* is arbitrary, although larger systems may be more complex to design. On the other hand, a smaller system may have more external dependencies.

When the item definition is in place, it is used as a basis for a *hazard analysis*. This analysis will produce a list of *hazardous events*, where each event is given an ASIL (Automotive Safety Integrity Level). The ASIL is an indication on how dangerous the event is, ranging from A to D, where D is most dangerous. An event may also be given the value QM which means that ASIL-related directives do not apply, and that normal Quality Management is enough.

Each *hazardous event* is then assigned to a *Safety Goal*, which is formulated so that when the goal holds, the event will not occur. The *Safety Goal* inherits the ASIL of the *hazardous event* that is assigned to it. Multiple events may be allocated to the same goal; if that happens, the *Safety Goal* inherits the highest ASIL of the set of events assigned to it.

From the *Safety Goals*, FSRs (Functional Safety Requirement) are derived. This could for example be done by an Fault Tree Analysis. The FSRs are in turn implemented by TSRs (Technical Safety Requirement). Each TSR can then be implemented by a *Software* or *Hardware*

Safety Requirement. The last two levels (i.e., hardware and software safety requirements) are however outside the scope of this thesis.

Each consecutive step in the process will have defined outputs. These are called *work products*. All the *work products* from the process are combined into a *Safety Case*, which together with written argumentation makes a case that the entire *item* indeed is safe.

Finally, it is worth to mention that ISO 26262 *only* concerns functional safety. There will be other requirements and considerations that must be taken into account for the system development, and these may be impacted by other standards or regulations.

Glossary

Acrolinx IQ	A tool succeeding the Scania Checker for the purpose of achieving consistent language in service manuals. 29, 55, 86
boilerplate	A template consisting of fixed syntax elements and placeholders for attributes. 31, 35, 46, 56, 63, 73–77, 79, 85, 92, 94, 95
CESAR Project	An European project with the title "Cost-efficient methods and processes for safety relevant embedded systems". 18, 30, 31, 35, 73, 74, 95
domain ontology	A domain specific ontology, i.e., a database with concepts and relations between the concepts. 31, 35, 55, 63, 76, 85, 92, 95
formal methods	Development methods with strong mathematical foundations which also employ formal notations. 17, 35, 47, 50, 56, 84, 87, 88, 91
formal notation	Defined by ISO 26262 as a "description technique that has both its syntax and semantics completely defined". 44, 47–52, 83, 84, 87, 94
functional safety	The absence of unacceptable risk to persons due to hazards caused by defects or bad design in an E/E system. 20, 21, 31, 34, 35, 84, 85
GLNQ	Predecessor of DODT. 31
informal notation	Defined by ISO 26262 as a "description technique that does not have its syntax completely defined". 44, 47, 84, 87
ISO 26262	The international standard ISO 26262 "Road vehicles – Functional safety". 13, 14, 20, 21, 23, 29, 32–36, 41–53, 56, 63, 70, 74, 79, 83–85, 92, 95
natural language	A language used to communicate between native-speaking humans. 16, 17, 31, 44, 46, 48, 52, 54, 67, 68, 73–75, 77, 78, 83–85, 87, 88, 91, 92, 94
Requirements Engineering	The field of gathering, specifying and managing requirements during system development. 16, 30, 34, 52
Scania Checker	A web-based tool used at Scania to increase consistence and quality in service manuals. 29, 86
Scania Lexicon	A corporate lexicon containing terms that are specific to Scania. 29, 35, 55, 63, 67, 86
semantics	The meaning of a word or a sentance. 16, 44, 46, 47, 54, 84, 94
semi-formal notation	Defined by ISO 26262 as a "description technique whose syntax is completely defined but whose semantics definition may be incomplete". 46, 51, 52, 84

Software Engineering	The field of constructing software systems in an organised way. 16, 48
stakeholder	A party with an interest in the outcome of a system or project. 13, 30, 42, 54
syntax	The set of rules defining how a sentence may be formed. 16, 31, 44, 46, 47, 54, 55, 65, 74, 84, 92, 94
Systems Engineering	The field of constructing entire systems, particularly those that include both software, hardware and humans, in an organised way. 16, 30, 34, 50

Acronyms

ASIL	Automotive Safety Integrity Level. 20, 42, 84
CNL	Constrained, or Controlled, Natural Language. 46, 54, 83, 88, 92
DODT	Domain Ontology Design Tool. 31, 35, 56, 58, 59, 63–65, 67, 69–79, 85, 86, 92, 95
E/E	Electrical/Electronic. 13, 20, 34, 35, 83
ECU	Electronic Control Unit. 35
FMEA	Failure Mode and Effects Analysis. 31
FSR	Functional Safety Requirement. 20, 51, 52
OCL	Object Constraint Language. 31, 95
OMG	Object Management Group. 31, 47
OWL	Web Ontology Language. 55, 64, 65, 67
RDM	Requirements Definition and Management. 43, 85, 86, 91, 94
SBVR	Semantics of Business Vocabulary and Business Rules. 31, 95
SG	Safety Goal. 51, 52, 63, 84
TSR	Technical Safety Requirement. 20, 51, 52
UML	Unified Modeling Language. 31, 47, 64
W3C	World Wide Web Consortium. 55

Part II:
Related work and method

4. Related work

While no material regarding requirement notations and ambiguity in relation to ISO 26262 has been found, there do exist a lot of research and other work that in different ways relate to this thesis. In this chapter, the work this thesis builds on is presented together with other relevant material.

4.1 The Scania Lexicon and other language tools

In the early 1990s, Scania started to use a digital catalogue for article numbers and their corresponding labels. The catalogue was named *Termlex*, which also contained the same terms in five different languages. Later on, *Termlex* was replaced by another application, *Termweb*, and given the name Scania Lexicon. At that point, the database was also cleaned up, definitions were added to the terms, and terminologists started to actively manage the contents. Today, Scania Lexicon is the official terminology database for Scania, containing not only article numbers, but also other terminology. The number of languages has grown from 5 to 21, and the Scania Lexicon is used both by engineers and by technical writers.

Starting in the second half of the 1990s, the After Market department at Scania and the Department of Linguistics and Philology at Uppsala University did a joint research project with the aim to be able to perform machine translation of truck maintenance documentation [6, 52]. Part of the project was to develop a constrained natural language titled *ScaniaSwedish*. While the original goal of automated translation was never achieved, the project resulted in a web based application named Scania Checker. The checker is described by Almqvist and Sågvall Hein [5] in the following way:

> Scania Checker is a language checker for automotive service literature in Swedish. It comprises a word checker and a grammar checker. A fundamental part of the wordchecker is a lexical database. [5]

The lexical database makes it easier for the technical writers to use a consistent vocabulary over time and in different documents. By using the lexicon, the Scania Checker is able to highlight – in different colours – rejected synonyms (red) and unknown terms (yellow). A third colour, green, is used to highlight grammatical errors. Almqvist and Sågvall Hein [5] also offers insight into how the Scania Checker was fit into the workflow at Scania. For example, the Scania Checker allows the writer to submit unknown terms for review and inclusion into the lexical database.

In 2011, work begun to phase out the Scania Checker in order to replace it with a product named Acrolinx IQ, which has support for integration directly into office tools like Microsoft Word and Framemaker. Additionally, it can be used to check that a text conforms with a predefined style. The new solution will use the same data that was initially collected for the Scania Checker and then refined over the years of continuous usage.

Although the checker is used for writing service manuals within the After Market department in Scania, there are at least two interesting aspects that relate directly to the field of systems development:

1. In both cases, it is important that a consistent vocabulary is used between all stakeholders. In fact, the After Market is a stakeholder to the high level system requirements because some of the information will, at a later stage, be incorporated into the service manuals.
2. As will be discussed later, using constrained natural languages (CNL) is a potential approach for writing better requirements. The knowledge and experience that the After Market department have gained in the area of language processing can be valuable also in other parts of the organisation.

There are of course some differences as well. The biggest one is that there are different underlying goals: for After Market, focus would be on automated document generation into multiple languages, while for system development, the focus would be on usable and unambiguous requirement specifications. For systems requirements, it may be acceptable to have rather terse sentences that not necessarily are what a native speaker is accustomed to. This might, however, not be such a good idea in a service manual with world-wide distribution.

Another difference is that for service manuals, the source language is Swedish. For software development, the language is mainly English, which also nowadays is the official corporate language within Scania.

4.2 The CESAR Project

The CESAR Project is a European project with 55 participating organisations mainly in the transportation sector. CESAR stands for "Cost-efficient methods and processes for safety relevant embedded systems" [14].

According to the project website, "CESAR will bring significant and conclusive innovations in the two most improvable Systems Engineering disciplines:

> Requirements engineering in particular through formalization of multi viewpoint, multi criteria and multi level requirements, ..." [14]

The focus on Requirements Engineering in the transportation sector makes the CESAR Project highly relevant for this thesis. Unfortunately, most of the project deliverables are restricted to the partner organisations, but two of the deliverables are available for the public and contains a wealth of information:

1. The SP2 (Requirements Engineering) report titled *Definition and exemplification of RSL and RMM* [12]
2. The SP3 (Component Based Development) report titled *Survey Report on Modeling Languages, Components Technologies and Validation Technologies for Real-Time Safety Critical Systems* [13]

Additionally, as some of the partners are academic institutions, the CESAR Project has also resulted in published research papers. Some of these are covered in the next section.

4.3 Domain ontologies and boilerplates

In the context of computer science, ontologies were first described by Thomas Gruber [24] for application in the artificial intelligence field. An *ontology* can be seen as a database of concepts with relations between them, and a domain ontology is an ontology which is specialised for a certain domain, for example the automotive industry.

In a research paper from 2006, Kaiya and Saeki [37] present a method for how a domain ontology can be utilised during requirements elicitation (i.e., the gathering of requirements). Two interesting aspects are that when concepts in the requirements are mapped to an ontology, it becomes possible to a) establish metrics of the requirements quality, and b) detect inconsistencies between the requirements.

Omoronyia et al. [42] extend the work of Kaiya and Saeki by researching how the process of building a domain ontology can be automated. They find that the manual effort can be reduced by importing domain specific documents such as standards and existing requirement specifications.

As part of the CESAR Project, Stålhane et al. [51] presents a tool, GLNQ, which combines the previous work on domain ontologies with the concept of boilerplates. Boilerplates were introduced by Hull et al. [27] and are predefined templates where certain attributes are inserted at specific placeholders in the text. Boilerplates also have similarities with the linguistic concept of *sentence stems*, which are described by Pawley and Syder [43]. Leeb-Lundberg [38] makes use of the sentence stem theory to investigate how students of law learn to use specific juridical terms.

Furthermore, Stålhane et al. [51] creates boilerplates based on requirements from the IEC 61508 functional safety standard. They also extend the information in the ontology in order to make it possible to describe potential *failure modes* for each concept. This allows GLNQ to output an FMEA (Failure Mode and Effects Analysis)-like table based on the concepts that are actually used in the requirements.

The work on safety analysis is extended in a more recent paper by Stålhane et al. [50] where GLNQ is superseded by the newer tool DODT (Domain Ontology Design Tool).

Finally, Farfeleder et al. [20] describe in some detail how DODT can be used for ontology-supported requirements elicitation.

4.4 SBVR and OCL

SBVR (Semantics of Business Vocabulary and Business Rules) [55] is an OMG (Object Management Group) specification which *"defines the vocabulary and rules for documenting the semantics of business vocabularies, business facts, and business rules"* [55]. It can be used to constrain the syntax of a natural language in a way similar to boilerplates.

OCL (Object Constraint Language) [56] is another OMG specification which was primarily designed to include formal constraints in UML (Unified Modeling Language) models. Warmer and Kleppe [58] describe how OCL works and presents a vision how it in the future could be used in a pure Model-Driven Development setting. They also argue that UML without OCL is ambiguous, and that the other way around is meaningless.

There are research related to OCL at the University of Birmingham. For example, Bajwa et al. [7] outline how natural language can be transformed to OCL statements by an intermediary SBVR step. According to a project website at the same university [57], there is also a tool that can transform natural language to the Alloy [4] specification language.

4.5 Other thesis projects at Scania

Performed concurrently with this thesis, there were also several other thesis projects at Scania that relate to ISO 26262. The one that is most relevant is the thesis by Erlandsson [19], which investigates the changes necessary to bring the existing requirement documents within Scania into compliance with ISO 26262. The thesis also contains a more in-depth discussion about requirements in general.

5. Method

This thesis was performed in a time period corresponding to 20 full time weeks and amounting to 30 Swedish university credits. The work was divided into five areas; each performed in parallel, but with varying intensity over time:

I. Understanding Scania

II. Understanding Requirements Engineering

III. Understanding ISO 26262 and Functional Safety

IV. Understanding formal methods

V. Performing a case study

Each area is described in more detail in dedicated sections at the end of this chapter. As can be expected, there were also some overlap as well as dependencies between the areas.

Since Scania use Lean or Agile-inspired work processes, it was from the beginning determined that a similar approach would be taken with the thesis project. This was particularly suitable since the topics covered in this thesis were new to both Scania and the thesis worker. In practice, this allowed the thesis to change direction as new knowledge was attained. As a consequence, the thesis does not cover exactly what was initially thought it would.

The original idea was to investigate formal methods as a means to achieve requirements that could be automatically verified. This included plans for evaluation a number of different formal methods in the context of a Scania system, in order to ultimately provide recommendations regarding their fitness for Scania. Additionally, since there is some buzz in the industry as well as academia regarding ADLs (Architecture Description Languages), it was suggested that the thesis should cover the possibility to express requirements in an ADL such as AADL or EAST-ADL.

However, it was relatively soon found that an adequate evaluation of several formal methods would require more time than what is possible in a master thesis project. It would also require prior experience with such methods. As for ADLs, they were found to be not applicable for the higher level requirements. Therefore, focus was shifted towards other areas.

Nevertheless, the original plans have to some extent influenced the thesis:

a) The objectives have been approached under the assumption that formal methods is a suitable solution to ambiguity, and also a possible means for automatic analysis.

b) Due to the formal approach, and of course also because this is an academic paper, a lot of effort has been made for finding exact and agreed upon definitions for concepts described in the standard.

The report itself was produced in an Agile-inspired manner where focus was on one chapter at a time. After completing a chapter and receiving feedback on it, focus was shifted to the next chapter. This approach was chosen because it was preferred to have fewer parts of high quality rather than many topics with less quality.

In addition to this thesis, there were three other thesis projects at Scania that studied different aspects of ISO 26262. Therefore, it was natural and indeed encouraged by the thesis supervisor at Scania that there were interactions and knowledge sharing between the different thesis projects as well as other relevant parties within Scania.

Finally, a couple of conferences and seminars on relevant topics were attended.

5.1 Understanding Scania

As was described in the introduction, a previous thesis performed a gap analysis between Scania and a draft of ISO 26262. This was used as a starting point for both understanding the environment within Scania and understanding ISO 26262. Other activities consisted of participating in internal meetings, study visits and thesis presentations.

It was also decided that an actual in-vehicle E/E system would be used as reference in order to have something to relate to when discussing ISO 26262 and other theoretical aspects. This is the same system as was used for the case study.

The system in question is the *fuel level display* which is responsible for measuring and displaying the vehicle fuel level and, if the fuel level falls below a certain threshold, display a low fuel level warning to the driver.

Another decision was to perform the daily work at the Scania R&D offices in Södertälje.

Overall, the above aspects gave insights into how Scania operates. It must, however, be pointed out that Scania is a very large company, and that it therefore would be ridiculous to claim a complete understanding of the entire corporation.

5.2 Understanding Requirements Engineering

Since both ISO 26262 and this thesis is focusing heavily on concepts from Requirements Engineering, and also because ISO 26262 in general do not explain the rationale between the various directives in the standard, it was necessary to gain an understanding on what the literature in the field recommended. In short, this meant that a lot of reading had to be done in order to get an enough background to be able to relate to the requirements in ISO 26262 and other standards.

Many of these books were revisited during the course of the project, and they proved to increase in value as various insights from the practical work were related to the concepts described in the books.

5.3 Understanding ISO 26262 and Functional Safety

As ISO 26262 is a standard oriented towards functional safety, it was imperative to gain an understanding about this concept. To achieve this, parts of the book *Safeware* by Leveson [40] were studied. It was early on found that functional safety has ties to Systems Engineering, wherefore a book on that topic was studied as well.

In order to understand ISO 26262, all master thesis workers with an interest in the standard participated in a study circle. This allowed for discussions where the attendees together could get a deeper understanding of the standard than by reading it individually.

Although it is not included in this thesis, the author did participate in creating a hazard analysis for the same system that is used as an example in the case study. This hazard analysis was done according to the directives in ISO 26262, and contributed much to the understanding thereof. The hazard analysis step is particularly important, since it is the initiation of the safety life-cycle, and the source from which all safety requirements are derived. In order to better understand the possible consequences of a potential system failure, some experiments with a real truck were done.

Overall, ISO 26262 is very extensive. The understanding of the standard did mature over time as different interpretations were discussed and discarded or refined. In some cases, external experiences from the EN 50128 standard for railways and the ISO 9001 were used in order to better understand ISO 26262.

5.4 Understanding formal methods

As was stated earlier in this chapter, the objectives were approached from the formal methods side, under the assumption that this approach, if no other, would be a viable solution for removing ambiguity. Therefore, a lot of effort was put into understanding what formal methods actually is, and for what problems and domains they are particularly useful for. To gain the desired understanding, both books and research papers were studied. Also, discussions with the reviewer of the thesis at Uppsala University were held, which were useful in order to keep on track and find suitable material.

5.5 Performing the case study

In order to provide concrete examples and also show that the results are relevant for Scania, a case study was performed where boilerplates and a domain ontology were applied to an existing vehicle system. The actual tool used for this is DODT. The technique was chosen for two reasons:

I. Scania already has a corporate dictionary with domain and company specific terms titled the Scania Lexicon (see Chapter 4) together with personnel to manage it. The experience and knowledge from the Scania Lexicon can be leveraged if Scania choose to further research the ontology concept. It may even be possible to use the same platform as the Scania Lexicon.

II. The research papers that are published about DODT and its predecessor GLNQ are aligned with functional safety aspects due to collaboration with the CESAR Project.

The system the technique was applied to was identified by Scania staff. It was deemed suitable because:

a) it is relatively small (only 4 ECUs (Electronic Control Unit) are involved),

b) it is not very complex (again, relatively speaking),

c) it is not overly sensitive in regard to intellectual property, and

d) the existing requirement and specification documents are considered representative for the majority of the E/E systems at Scania.

During the case study, care was taken to follow, to the extent it was possible, the workflow prescribed in ISO 26262. The results, and also a more detailed description on how the study was performed are available in Chapter 9.

Part III:

Current and future practices

6. Structure and elements of requirements

This chapter begins with a motivation for why requirements are important for software and system development, including some comments on how requirements relate to Agile and Lean. This is followed by a compilation of requirements on the requirements themselves, both individually and as a set.

6.1 Why requirements matter

An in-depth discussion on the merits of good requirements and requirements management is outside the scope of this thesis. However, there are a lot of literature indicating that missing or bad requirements commonly is responsible for late or failed projects. For example, according to Bowen and Hinchey [10], data from NASA shows a strong correlation between project cost overruns and too little time spent on requirements. Glass [22], in his book *Software Runaways* state the following:

> Study after study has found that where there is a failure, requirements problems are usually found at the heart of the matter. [22]

In addition to cost overruns, lack of requirements can also lead to harm, including loss of life:

> In an investigation of failed safety-critical systems, one study found nearly 1,100 deaths attributable to computer error. Many of these errors stemmed from poor or no specifications, not an incorrect implementation. [10]

Finally, without requirements, it makes no sense to speak about verification or validation, because there is nothing to verify against.

6.2 Using requirements throughout the process

Requirements are not something that should be done early on and subsequently left static during the development process. As the work progress downwards in e.g., the V-model, new information will be found which can result in compromises in existing requirements. New requirements may also be discovered during the process that was not though of initially.

After the requirements are written, the next step in the development process is to create an architecture or design of the system. Both “architecture” and “design” are words that are used intermixedly and with different meanings. This thesis uses both in the broader sense of establishing a logical or physical structure of the components or parts of a system.

Unfortunately, it is not uncommon that the requirements phase is reduced or altogether ignored, because creating a design is perceived as real work, while writing requirements are not.

Sometimes, it is said that developers do not like requirements because it takes the creativity out of their work. If that is the case, then the requirements are not written correctly. A requirement should state *what* the system should do, not *how*. Overspecification can be as bad as underspecification, because it might restrict the developers from finding the best possible solution to the problem.

6.3 Requirements, Lean, and Agile

Some proponents of Agile methods appear to use Agile as an excuse to avoid doing requirements at all. The following seems to be a common argument "Since everything might change during the process, there is no need for any requirements, since those too will change."

However, change does not exclude requirements. As Alexander and Stevens [3] write:

> [. . .] expecting change is not an excuse for not doing the requirements well. The more you find out about what the users want early on, the less needless change there will be in the requirements, and the less the project will cost. [3]

Agile methods such as Scrum, do make use of requirements. The difference is that it is called sprint or product backlog instead of requirements, and that the prioritisation is allowed to be volatile.

Agile is also influenced by Lean, and the primary Lean principle is to *eliminate waste* [44]. Without good requirements, the developers have no guidance on what to develop, which means that functionality that is unneeded may be included. This is, by Mary and Tom Poppendieck, considered as *serious waste*:

> Eliminating waste is the most fundamental lean principle, the one from which all the other principles follow [. . .]
>
> It may seem like a good idea to put some extra features into a system just in case they are needed [. . .] This may seem harmless, but on the contrary, it is serious waste. Every bit of code in the system has to be tracked, compiled, integrated and tested every time the code is touched, and then it has to be maintained for the life of the system. Every bit of code increases complexity and is a potential failure point. [44]

As with everything else, there is no method that is best for everything. While the volatile requirements approach used by Agile methods such as Scrum may be highly suitable for user interface development, it may not be equally suitable for a safety critical system. In the latter case, the impact of a requirements change during the process may be higher. For example, changing a key feature of a system could require that a new hazard analysis must be performed, and in turn that new safety goals must be added. This would likely affect the entire architecture, leading to higher costs and delayed delivery.

6.4 Properties and attributes of requirements

The difference between a *property* and an *attribute* is that a property describe a characteristic, i.e. something that that the requirement *is*, while an attribute can be said to be something the requirement *has*, i.e. something that can be attached or annotated to it.

The properties and attributes listed in this section comes from the five sources listed in Table 6.1. There are of course a lot of more sources available; nor are the chosen sources exhaustively covered; there are additional considerations in all of them. The purpose of the choice is to include perspectives both from industry and academia in order to highlight some of the most important or most commonly asked for characteristics of requirements.

Table 6.1. *Sources for requirements*

Label	Description	Ref
CESAR	The CESAR *SP2 Report*	[12]
CMMI	The SEI *CMMI for Development, Version 1.3*	[16]
IEEE	The IEEE *Std 830-1998*	[28]
ISO	The ISO *FDIS 26262*	[31]
HULL	The book *Requirements Engineering* by Hull et al.	[27]

A few points on the nature of these sources may be needed for clarification:

- ISO 26262 has a special importance due to the objectives of this thesis; the requirements therein are considered mandatory, but *only* for safety-related requirements. However, for the majority of requirements, it is sensible recommendations that also are in-line with other sources.
- IEEE Std 830-1998 describe the overall characteristics of a SRS (Software Requirements Specification), i.e., more concerned about sets of requirements rather than properties of each unique requirement. Nevertheless, necessary properties for individual requirements are in many cases described within the context of the entire specification.
- SEI CMMI is about development processes and do not explicitly describe individual requirements. However, some guidance on requirement properties and attributes is provided. In other cases, properties can be deduced from the process requirements.

As can be expected, the different sources sometimes have different terms for the same concept. In those cases, the alternative provided by ISO 26262 is used.

6.4.1 Individual requirements

Each requirement should at least have the properties listed in Table 6.2.

Table 6.2. *Properties of individual requirement*

Property	Description	Sources
Unambiguous	The requirement has only one interpretation.	CESAR, IEEE, ISO
Comprehensible	All stakeholders are able to understand the requirement.	ISO
Atomic	The requirement cannot be split into two or more requirements.	HULL, IEEE, ISO
Consistent	The requirement does not contradict itself.	ISO
Feasible	The requirement can be implemented within the constraints of the project or organisation.	CESAR, CMMI, HULL, ISO
Verifiable	It is known how to, and practically possible, to verify that the produced artefact meets the requirement.	CESAR, CMMI, HULL, IEEE, ISO

The properties are not enough it themselves; it is also necessary to be able to attach additional information, referred to as *attributes*, to each requirement. The following attributes are recommended by one or several sources, or required for safety requirements by ISO 26262:

Table 6.3. *Individual requirement attributes*

Attribute	Description	Sources
Unique identifier	The requirement has an unique identifier.	CMMI, HULL, ISO
Safety requirement	If it is a safety requirement, it is flagged as such.	ISO
Status	The requirement has a *status*, for example *proposed* or *approved*.	CMMI, ISO
ASIL	If it is a safety requirement, it must have an ASIL.	ISO
Importance	The importance of the requirement, e.g., *optional* or *essential*	CMMI, HULL, IEEE
Stability	A measure on how likely the requirement is to change.	IEEE

6.4.2 Sets of requirements

A set of requirements can for example be a document such as the SRS described in IEEE Std 830-1998. In this thesis, however, it will be used mainly in the context of an *item* as described by ISO 26262. In other words, the set of requirements will be all the requirements that pertain to a particular *item*. The required characteristics for a set of requirements are listed in Table 6.4

Table 6.4. *Characteristics for sets of requirements*

Property	Description	Sources
Hierarchical structure	The requirements are organised in levels according to the life-cycle.	ISO
Complete	The set of requirements at one level fully implements the requirements on the previous level.	ISO
Consistent	No requirement contradicts any other requirement in the set.	CMMI, HULL, IEEE, ISO
No duplicate information	Accordning to ISO 26262, there may be "no duplication of information within any level of the hierarchical structure [31]".	IEEE, ISO
Maintainable	It is possible to add or remove new requirements as well as creating new revisions of existing requirements.	CMMI, IEEE, ISO
Traceable	Each requirement is traceable to both the source at an upper level as well as any lower level requirements derived from it. This is also referred to (by IEEE) as *backward* and *forward traceability*, respectively.	CMMI, IEEE, ISO

6.5 Documents are no longer sufficient

The IEEE *Std 830-1998* [28] and books like *Requirements Engineering: A Good Practice Guide* by Somerville and Sawyer [49] spend a lot of effort to describe how sets of requirements should be organised in various documents. The term *specification* seems to be implicitly associated with an artefact in the form of a document.

Although a set of requirement sooner or later is likely to appear in a form close to or identical to a document, it is doubtful that it is adequate to *store* the source information in e.g., Word or Excel documents. The reason is *traceability*.

If compliance with ISO 26262 is desired, then Paragraph 6.4.3.2 in Part 8 must be adhered to:

> **6.4.3.2** Safety requirements shall be traceable with a reference being made to:
>
> a) each source of a safety requirement at the upper hierarchical level,
>
> b) each derived safety requirement at a lower hierarchical level, or to its realisation in the design, and
>
> c) the specification of verification in accordance with 9.4.2.

Add to this that each requirement must be uniquely identified throughout the life-cycle, the demands for *Change management* in ISO 26262-8 Clause 8, and the demands for impact analysis for changes in ISO 26262-8.

While it of course is theoretically possible to achieve the above with Word or Excel, it will become an administrative nightmare in reality. A solution could be to deploy a RDM (Requirements Definition and Management) system. This is discussed in more detail in Chapter 10.

7. Notations for requirements

Requirements can be specified in varying degrees of formality. They can also be represented in different forms such as text, symbols, or graphics.

Note well: the formality and the form of representation are orthogonal. Mathemathical symbols can be used informally, and normal words can be used in a highly formal manner. This distinction made, it is however more common that mathematical symbols are used in more formal notations. Graphics is used in all levels of formality, from a quick drawing on a whiteboard during a meeting, to a completely formalised state machine.

Different degrees of formality and forms of representation can also be combined. Each method or combination thereof may be more or less suitable for a particular organisation, and the suitability of a given method can also vary between the various phases in the development process.

7.1 Levels of formality

The degree of formality for a given notation can be divided into three levels: *informal*, *semi-formal* and *formal*. The difference is to what extent the syntax and semantics is defined. As the degree of formality increase, the ambiguity typically decreases. The definition in the beginning of each subsection below is taken from ISO 26262-1 [31].

7.1.1 Informal notation

Definition:

> description technique that does not have its syntax completely defined
>
> EXAMPLE Description in figure or diagram.
>
> NOTE An incomplete syntax definition implies that the semantics are also not completely defined. [31]

The most common informal notation is probably natural language (commonly referred to as NL), i.e. English or Swedish. There is one major advantage with NL, namely that everyone can read and understand it. On the other hand, natural language is inherently ambiguous [28], which contradicts the proposition that everyone can understand it: it would probably be more correct to say that everyone have *their own* understanding of it.

Take for example the following requirement from the requirements document for the existing *fuel level display* system:

If the fuel level sensors have electrical errors such as short circuit a DTC should be created. [47]

While it may appear to be clear and concise at a glance, there are some problems with it:

- The word *"should"* is often used in spoken language to mean *shall*. In requirement specifications, *should* is by convention used for optional features that are desirable but not strictly mandatory. It is not obvious whether or not the author of the requirement was aware of this distinction at the time of specification.
- The components *"fuel level sensors"* are not defined elsewhere in the requirements document. Are the sensors part of this system or another? How many sensors are there? Is the sensor mount point in the tank included in the concept "sensor"? Does the cabling between the sensor and the A/D-converter belong the sensor?
- Which *"electrical errors"* are intended? Is it only errors in the sensors that should be detected? What about the cabling between the sensor(s) and the ECU(s)? If all cables are cut or if the connector comes loose, is that an electrical error as well? If it is a short-circuit, how long must it persist before it is considered an error? What about the feed current to the sensor; is interrupted power supply an electrical error?
- *When* is the DTC (Diagnostic Trouble Code) supposed to be created? Is there a time limit? Are there limits for how many DTCs that can be created for a particular error?

If multiple requirements with similar ambiguities are combined into a system specification, it is reasonable to assume that the developers would make their own interpretations on how the system actually is supposed to behave. This can have one or several adverse effects such as:

1. Intended functionality is not implemented because the developer does not think it is required. This could cause accidents or dissatisfaction among the customers.
2. More functionality than was intended is implemented. This would make the system both more complex and more expensive than necessary, which has safety implications because a complex system is harder to understand and also generally contains more defects [44]. Recall also the quote by Poppendieck regarding waste (see Chapter 6).
3. ISO 26262-6 Clause 11 mandate verification against the requirements. This verification must be done by a person or team independent from the developers (see ISO 26262-2 Clause 6). If the verifiers interpret the requirements differently from the developers, it could cause both expensive rework or delayed start of production. The later in the process a necessary change is detected, the more costly will it be to implement it (see Chapter 6). The verifiers could alternatively get the impression that the system is supposed to do less than what it actually does and therefore fail to verify important functionality, potentially leading to accidents. In both cases, the value of the verification is reduced.

Another example of the ambiguousness inherent in natural languages is presented by Cooke [17]:

When travelling on the London Underground, you will see the sign:

'Dogs must be carried on the escalator.'

[...] Can you imagine the chaos that would ensue if you had to find a dog to carry before you stepped on to the escalator, [...]

Although the above may be seen as a toy problem, it is a good example of how easy it is to include unstated assumptions in natural language, assumptions that may not be shared by all stakeholders. To be able to write good requirements in natural language, discipline, previous experience from requirements and solid language skills are needed, but even that may not be enough to avoid ambiguity.

7.1.2 Semi-formal notation

Definition:

> description technique whose syntax is completely defined but whose semantics definition can be incomplete
>
> EXAMPLE System Analysis and Design Techniques (SADT); Unified Modeling Language (UML). [31]

ISO 26262 does not define "syntax", and much less what a "completely defined" syntax is. In the linguistic tradition, syntax is usually defined in a similar manner as was stated in Chapter 2: *"The* syntax *of a language is a system of grammar laying out rules about how to produce or recognize grammatical phrases or sentences."* [26].

What, then, is "completely defined" syntax? Drawing inspiration from the field of formal languages and also the book *Concepts of programming languages* [48], this thesis will use the following definition:

DEF: The syntax of a language L is *completely defined* if and only if, for any string S, it can be determined without doubt whether or not S is part of L.

Using the above definition, most programming languages have completely defined syntax. It is also possible to impose strict enough rules on a natural languages to comply with the above definition. Such languages are intermixedly referred to as *Controlled* or *Constrained Natural Language*. Both are abbreviated as CNL. A CNL can also be less restricted than the definition above and still be referred to as CNL. One such example is *ScaniaSwedish* which was described in Chapter 4.

An example of a CNL, which is targeted directly against requirements, is the concept of boilerplates. As was described in Chapter 4, a boilerplate can be seen as a template containing fixed syntax elements and attribute placeholders. The following two boilerplate statements

> *While* <operational condition>
> *the* <system> *shall* <action>

have <operational condition>, <system>, and <action> as attributes, and can for example be combined into

> *While* <the vehicle fuel level is less than the low fuel level threshold> *the* <fuel level display system> *shall* <present the low fuel level warning to the driver>

The advantage with semi-formal notations is that the complete syntax can limit the variation of the expressed requirements, which could force the requirements to be formulated in a more concise and consistent manner. Care must however be taken so that the expressiveness not is reduced too much – it must still be possible and also easy enough to convey the desired meaning.

The disadvantage is the lack of completely defined semantics. There is therefore still a risk that different individuals will make disparate interpretations. Graphical notations are not an exception. Consider the well-known adage "one picture says more than a thousand words" in context of ambiguity: a single requirement consisting of a thousand words could easily have more than one interpretation. As Jackson [32] puts it:

> The cure is to be very careful when you write a description in any language, and to be twice as careful again if it's a graphic language. [32]

UML (Unified Modeling Language), which is given as an example by ISO 26262, merits some additional commentary since it is well-known and used for various purposes by many IT professionals. UML is an OMG (Object Management Group) standard. The current official version (2.3) consists of two different specifications, the *Infrastructure* [53] and the *Superstructure* [54], which together amounts to about 1000 pages of text mixed with figures. This extensiveness may be due to the history of UML. Bowen and Hinchey [10] make the following remark:

> Another caveat to using UML is that it essentially standardizes several existing and emerging graphical notations for system specification [. . .] Some of these are there for good reason; others, because they had support from particular quarters. [10]

Since there are 14 diagram types – of different origins and therefore lacking common design principles – it can be quite difficult to determine whether a given diagram comply with the UML specification or not. Although it is certainly possible to read the specification itself and try to compare it with the diagram, it is hard to get a clear picture of what is allowed and what is not. The reason for this is that the specification is written in a way that makes it hard to be sure in what context a given element may be used. The situation is not helped by the fact that is allowed to include parts, or the whole, of a diagram into a diagram of a different type.

Consequently, if it is hard to be certain whether a specific diagram conforms to the syntax or not, there is a risk that UML, for all practical purposes, is no better than an informal notation .

7.1.3 Formal notation

Definition:

> description technique that has both its syntax and semantics completely defined
>
> EXAMPLE Z (Zed); NuSMV (symbolic model checker); Prototype Verification System (PVS); Vienna Development Method (VDM). [31]

ISO 26262 does not further define *completely defined semantics*, but based on the term "description technique" and the provided examples, the standard seems to equate formal notations with formal methods (see Chapter 2). While the two terms are closely related, this thesis makes the distinction that a formal notation is the notation used by a corresponding formal method. By implication, *completely defined semantics* then means that the notation can be transformed into a mathematical system where proofs can be performed.

There is yet another related term that needs clarification, namely formal specification, which is here defined as the artefact created when a formal notation is deployed to specify a system. In other words, a formal specification *contains* formal notation, and *may* have been produced using a formal *method* or *technique*.

The main advantage with formal notations is that there, by the ISO 26262 definition, can be no ambiguity. This makes it possible to establish, without doubt, whether a system conforms to its specification or not, without arguments or confusion on what the requirements actually mean. This also makes such requirements suitable for legal contracts with external suppliers.

On the other hand, it is commonly held that formal notations are hard to understand and requires training before they can be used:

> One disadvantage in the use of such languages is the length of time required to learn them. Also, many non-technical users find them unintelligible. [28]

Both points are valid. However, as was mentioned earlier, being able to formulate good requirements in natural language is far from easy and requires both training and experience. Similarly, it is unreasonable to expect a developer to produce quality code in new programming language without prior training. The same should apply for requirements specification languages, formal or otherwise.

Of course, someone outside the field of Software Engineering should not be required or expected to understand formal notations. Therefore, an accompanying translation into natural language is needed:

> [. . .] someone must fully explain formal specifications so that they are understandable to both nonspecialists and those working on the specification after its initial development. [10]

Producing a natural language version from a formal notation also have other advantages:

> This effort is worthwhile, since our experience has shown that documents produced from a formal specification can be more comprehensible, more accurate, shorter, and more useful than informal specifications. [25]

Although the above quote is about manual transformation, it should also be possible to automate this process since, after all, the notation is unambiguous. Each statement could then also be output in different languages, depending on capabilities of the tool used for the task. A further study about automatic natural language generation is outside the scope of this thesis.

The crucial question is whether formal methods are worth the effort. It is important to be aware that formal methods are not “all or nothing”; rather, they can be employed to different degrees in various phases. For example, Bowen and Hinchey presents three different levels, where each subsequent level builds on the previous one. This is shown in Table 7.1.

Since this thesis mainly is concerned with requirements, focus will be on level 0. This is also the level where most organisations stand to gain the majority of benefits if they not already are using formal methods. The two subsequent levels can of course provide further

Table 7.1. *Formalisation levels according to Bowen and Hinchey [10]*

Level	Name	Involves
0	Formal specification	Using formal notation to specify requirements only; no analysis or proof
1	Formal development/ verification	Proving properties and applying refinement calculus
2	Machine-checked proofs	Using a theorem prover or checker to prove consistency and integrity

benefits, but seems to be used mainly by organisations developing safety-critical systems [59].

Summarising the various advantages gained by using formal methods at the specification level, three main benefits can be discerned (the advantages are described in more detail below):

a) reduced cost,

b) improved quality and

c) improved safety.

Quality, in this case, is used in the sense of internal system properties such as few number of bugs and robust architecture. Although safety can be seen as one of many quality properties, it is here treated explicitly. This is because safety is an important concern of both ISO 26262 and this thesis.

Most of the benefits arise from the fact that using formal notations for requirements makes it necessary to know what the system is supposed to do at the time of specification:

> The use of mathematically based approaches has great potential to help eliminate errors early in the design process. It is cheaper than trying to remove them in the testing phase or, worse, after deployment. Consequently, it is true that using formal methods in the initial stages of the development process can help to improve the quality of the later software, even if formal methods are not used in subsequent phases of development. [10]

According to Bowen and Hinchey [10], formal methods "demand quality documentation" such as rationale for particular design decisions. This obviously contributes to all three benefits above, because a well-documented system is easier to maintain (cost and quality), and the risk of introducing a safety-related bug is reduced if the developer knows *why* the system is designed as it is.

Another advantage raised by Bowen and Hinchey [10] is improved reusability, which can reduce cost if done correctly. The improvement from traditional reuse is that:

- It is easier to find a suitable module for integration. This is because it is possible to read the specification and thus be sure about the input the module expects and the output it provides (of course under the assumption that the module has been verified against its specification).
- It is possible to reuse the specification itself for developing identical behaviour on different platforms.

Both cases improve modularity. Safety and quality aspects are also improved if a low number of well-written and self-contained components are reused rather than reinvented in multiple systems. Additionally, Jézéquel and Meyer [33] argue that it is likely that the *Ariane 5* disaster could have been avoided if the pre- and postconditions had been an integral part of the software component. Although Jézéquel and Meyer propose a technique called Contract-Based development, formal specifications also exhibit the same type of strict pre- and postconditions, and so should be able to achieve the same result.

Finally, safety is where formal methods really shine due to the possibility to mathematically reason about the behaviour of the system, and if desired, also perform proofs [25]. It is not unreasonable to assume that this is the reason why some safety standards mandate the use of formal methods [10]. Nevertheless, not all types of systems or requirements are suitable for formal notations; one such example is user interface design [10]. There are many different types of notations, formal or otherwise, each having its own strengths and weaknesses compared to the others. A suitable set of methods and techniques must therefore be applied for each specific project and system.

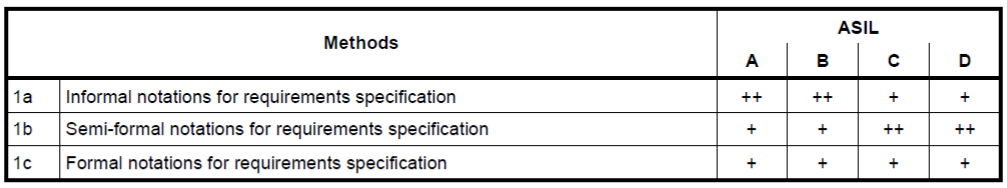
To sum up this section, it must be noted that while there are good reasons to use formal notations, they are not a panacea against all the problems inherent in software and Systems Engineering. Although formal methods can be used to prove correctness in regard to the specification, it does not necessarily mean that correctness in regard to the real world is achieved [25]. If the requirements does not specify the desired system, then no method, formal or otherwise, can help. Neither should formal methods supplant current development processes or existing quality standards, but by integrating those in the current work processes, it is possible to reap the benefits from both worlds [10].

7.2 Directives from ISO 26262

The most relevant source regarding requirements in ISO 26262 is Part 8 Clause 6:

> **6.4.1.1** To achieve the characteristics of safety requirements listed in 6.4.2.4, safety requirements shall be specified by an appropriate combination of:
>
> a) natural language, and
>
> b) methods listed in Table 1.
>
> NOTE For higher level safety requirements (e.g. functional and technical safety requirements) natural language is more appropriate while for lower level safety requirements (e.g. software and hardware safety requirements) notations listed in Table 1 are more appropriate.

Table 1 — Specifying safety requirements



Methods		ASIL			
		A	B	C	D
1a	Informal notations for requirements specification	++	++	+	+
1b	Semi-formal notations for requirements specification	+	+	++	++
1c	Formal notations for requirements specification	+	+	+	+

To be able to interpret the table, ISO 26262 Part 8 Section 4.2 (*Interpretation of tables*) is needed:

> For alternative entries, an appropriate combination of methods shall be applied in accordance with the ASIL indicated, independent of whether they are listed in the table or not. If methods are listed with different degrees of recommendation for an ASIL, the methods with the higher recommendation should be preferred. A rationale shall be given that the selected combination of methods complies with the corresponding requirement.

NOTE A rationale based on the methods listed in the table is sufficient. However, this does not imply a bias for or against methods not listed in the table.

For each method, the degree of recommendation to use the corresponding method depends on the ASIL and is categorized as follows:

- ++ indicates that the method is highly recommended for the identified ASIL;
- + indicates that the method is recommended for the identified ASIL;
- o indicates that the method has no recommendation for or against its usage for the identified ASIL.

The above is slightly ambiguous. It both states that there is "no bias for or against" any of the methods, and that methods with higher recommendations "should be preferred". A common interpretation at Scania is that methods marked with "++" must be performed, while anything less can be done if so is desired, but it is not strictly necessary for compliance.

An interesting issue arise when *Table 1* in the cited clause is studied in detail. For ASIL C and D, by the given interpretation, semi-formal notation is to be used. Would it be equally acceptable to go one step further and instead use formal notations? A formal notation fulfils, according to the definition in ISO 26262, everything that a semi-formal notation does. The difference is that a formal notation also has completely defined semantics. It seems reasonable that an organisation should be allowed to use a formal notation as a replacement of a semi-formal notation because:

a) Semi-formal notations are subsets of formal notations according to the definitions given in ISO 26262.

b) A formal representation can, if so desired, easily be transformed into a semi-formal one. The easiest way, but perhaps not the most sensible, would be to simply state that the formal portion of the notation is not taken into account.

c) It seems counterproductive to restrict the usage of the most exact methods when the goal is to improve functional safety.

This does of course not mean that such a substitution should be done in every case; the key point is that it is *possible* to do so. The above points could be sufficient as a rationale according to the standard, but the decision will ultimately be in the hands of the assessor.

As was stated in the objectives in Chapter 1, this thesis is primarily concerned with higher level requirements. Therefore, a more detailed analysis about the directives regarding these types of requirements is merited. Consider again the note from Paragraph 6.4.1.1 in ISO 26262-8:

NOTE For higher level safety requirements (e.g. functional and technical safety requirements) natural language is more appropriate [...]

Although the note only lists FSRs (Functional Safety Requirement) and TSRs (Technical Safety Requirement), it can be assumed that SGs (Safety Goal) also belong to the category *higher level requirements*. This assumption can be motivated because *a)* it is not specified elsewhere in the standard how SGs should be written, and *b)* the following note from ISO 26262 Part 3, Paragraph 7.4.4.3:

NOTE Safety goals are top-level safety requirements for the item [...]

At this stage, the following observation can be made:

ISO 26262 has a bias for specifying SGs, FSRs and TSRs in natural language.

To complicate matters, this bias contradicts another part of ISO 26262-8 Clause 6, namely Paragraph 6.4.2.4:

> **6.4.2.4** Safety requirements shall have the following characteristics:
>
> a) unambiguous and comprehensible,
>
> NOTE 1 A requirement is unambiguous if there is common understanding of the meaning of the requirement.
>
> NOTE 2 A requirement is comprehensible if the reader at an adjacent abstraction level (i.e. either the stakeholder or the consumer of that requirement) understands its meaning.

The contradiction lies in the inherent ambiguousness in natural languages, which was illustrated in the previous section. Formulated in other words, ISO 26262 states that it is appropriate to use an *inherently ambiguous* notation in order to write *unambiguous* requirements.

No rationale for the preference for natural language is given, but from the note about comprehensibility and also Requirements Engineering literature such as [3], it could be assumed that the main reason is that SGs, FSRs and TSRs should be readable without requiring training in formal or semi-formal notations. Recall, however, that that use of formal notation should come with associated natural language narrative, so they are by no means exclusive.

To further complicate matters, a requirement written in a semi-formal CNL could very well be indistinguishable from a natural language when it is seen by the reader; the constraints are imposed mainly on the writer. It could be argued that such an approach is more appropriate than (informal) natural language due to the inherent ambiguity in the latter.

From a compliance perspective, it would depend on how literal-minded the assessor would be, and whether he or she would interpret the directives to mean the the resulting requirements, or the process of writing them.

Another observation that is worth to point out explicitly is the following:

ISO 26262 does not state that natural language has to be the only *representation for the higher-level requirements.*

As was described earlier, there are many benefits associated with using formal methods for requirements specification. If such notations are used together with natural language versions (i.e. different versions exist for an individual requirement), it must be decided and communicated which version that has precedence. Due to the preference towards natural language in ISO 26262, the interpretation could be that the NL version should take precedence. However, Bowen and Hinchey [9] advocate the opposite:

> If there is any discrepancy, the formal specification takes precedence because it is the more explicit of the two descriptions. [9]

It is also easier to test against a more precise requirement, which means that verification testing might be done against the formal version. If that is the case, it makes additional sense to let that version have precedence. Nevertheless, doing so could risk noncompliance with ISO 26262, even though the motivation behind the standard is to increase safety in the systems that are to be developed.

8. Semantics and domain knowledge

8.1 The need for semantics

As was mentioned in Chapter 7, requirements can be specified in constrained natural language CNL. Depending on the syntax definition, such a CNL may also be semi-formal. While this can be an improvement to (informal) natural language, it is not necessarily enough for achieving high quality requirements. Consider the following boilerplate requirement (which arguably could fall in the category of a semi-formal CNL):

> *While* <the vehicle fuel level> *is less than the* <low fuel level threshold> *the* <fuel level display system> *shall* <present> <the low fuel level warning> *to* <the driver>

The improvement over natural language comes from the imposed overall structure due to a limited syntax; it is clear that *something* is supposed to occur while a certain condition holds. However, the same type of problems with ambiguity as was shown in Chapter 7 still exist. For example, what exactly is *the vehicle fuel level*?

- Is it the *actual* fuel level in the tanks, or is it the *usable* fuel level? If the latter, is the *usable* fuel level identical to the fuel that can actually be extracted from the tank, or could *usable* also mean fuel that it is not mixed with too much water?
- What does *level* mean? Does it have a unit? Is it a volume? Is it the ratio between two volumes, e.g., the ratio between the current fuel volume and the maximum tank volume?

This list with questions could go on and on for each individual concept in the requirement. Although it might be seen as academic nitpicking, it is the very type of questions that must be answered in order to build a system. If the meaning is not made explicit in the requirements, there is a risk that the developer(s) could make another interpretation than the stakeholders, which in turn can lead to one or more adverse effects as outlined in Chapter 7.

A second problem arise when various automatic processing of the requirements is considered. Such processing could for example be automated consistency analysis or machine translation. Take the word *"driver"*; it could be replaced by an arbitrary string like *"happiness"*. It is still syntactically correct but it does not make much sense. Even more challenging, it could be a word like *"seagull"*, which *could* make sense, but is very implausible to do so in the context of a fuel level display.

To overcome the above challenges, information about the semantics must somehow be included in the requirements.

8.2 Improving communication

A first step for solving the problem with ambiguous concepts could be to include a glossary in the requirements document. In this way, the reader can look up terms that he or she is unfamiliar with. This practice is recommended by IEEE [28] as well as literature [49]. There are however some problems with this approach:

1. A reader might not always look up concepts that he or she is familiar with, thus missing that the author in fact has an altogether different interpretation of it.
2. A concept might change meaning over time, but not become updated in every document it is used in, thus causingdiscrepancies between the written documents and the institutional knowledge.

The importance of achieving a common understanding of a concept between stakeholders and developers cannot be stressed enough. What is needed is some sort of knowledge base which both writers and readers of the requirements have readily access to. Such a knowledge base could exist as a stand-alone lexicon, but it could also be integrated into tools supporting the writing of documents. Ideally, it would be integrated with any information management tool used throughout the system life-cycle.

An example of a stand-alone knowledge base is the Scania Lexicon which was covered in Chapter 4. The same information is also used by the Acrolinx IQ product which provides integration with writing tools such as Word and Framemaker.

8.3 Towards automated reasoning

A lexicon is however not enough for allowing automated reasoning. Even if the syntax is made strict to the degree that only words existing in the lexicon may be inserted into a requirement, a computer system will still not be able to detect words in the lexicon that do not make sense in the given context. The below requirement would be perfectly acceptable by such a system as each concept is taken from the Scania Lexicon:

> *While* <the fuel level> *is less than* <the gearbox> *the* <bumper> *shall activate* <the direction indicator>

Obviously, a lexicon-based approach is not sufficient to ensure useful requirements in itself. If a computer is to be able to analyse a requirement, there must also exist relations between the concepts. One way to achieve this is to use domain ontologies, which were introduced in Chapter 4.

Ontologies can for example be specified in OWL (Web Ontology Language) [60], which is a W3C (World Wide Web Consortium) specification. OWL ontologies are built upon three basic notions:

- *Axioms*, which are statements or propositions of basic knowledge that are either true or false.
- *Entities*, also referred to as *concepts*, that define the objects that are described.
- *Expressions*, also referred to as *relations*, which connects the entities (or concepts).

A reader that is familiar with Object Oriented Design (OOD) will find similarities in OWL; for example, a concept has a correlation to a *class*, and there is also a *subclass*-axiom available. There are also important differences; in OOD, it would probably be considered poor design to create two identical classes, and then somehow mark those as identical. However, this is a very useful feature in an ontology, because it makes it possible to mark one of the concepts as deprecated. This is useful in a lexicon where there are different terms for the same thing, but it is desirable to use only one of them.

If a sufficiently detailed ontology exist, a requirements analysis tool could be "aware" that the fuel level display system is related to a *user* concept, and more specifically to a specialisation *driver*, but not to *"happiness"* or *"seagulls"*. If the ontology is also combined with boilerplates, a tool could be able to detect boilerplate attribute values that do not make sense in a given context.

Of course, in the same manner that formal methods is no panacea, neither are ontologies. The perhaps greatest challenge is the establishment and maintenance of the contents in the ontology. On the other hand, Scania has an advantage here due to their long experience with language technology (see Chapter 4). Additionally, Omoronyia et al. [42] found that the process could be simplified by automatically parsing and importing technical documents, preferably standards, into an ontology. Functionality towards this end is also being developed in DODT.

Nevertheless, there is no doubt that it will take considerable effort to build and maintain an enterprise-wide ontology, even though parts of the process might be automated. However, if it can be done, the ambiguities in requirements could likely be reduced, automated translation made more feasible, and understanding between different parts of the organisation be improved.

8.4 Requirements metrics

An advantage that can be gained from using ontologies is that it becomes possible to calculate metrics on a set of requirements that are mapped to ontology concepts or relations.

8.4.1 Metrics by Kaiya and Saeki

In a paper on using domain ontologies for requirements elicitation, Kaiya and Saeki [37] presents four different metrics which are discussed in more detail below. An even more detailed mathematical description is available in a previous paper by the same authors [36]. A few explanations are necessary in order to understand the definitions in this section:

- An "ontological element" can be both a concept and a relationship between concepts.
- A "set of requirements" can for example be all the requirements in a system specification, or all the requirements associated with a particular *item* in ISO 26262.
- When a "requirement maps into the ontology", the actual mapping is in fact between a constituent word of the requirement text and an ontological element. For example, nouns are usually mapped to ontology concepts, and verbs to ontology relationships. Note that while there can be multiple mappings from within one requirement, the entire requirement is still considered to map only once.

Correctness (COR)

If all requirement in the set are mapped into the ontology, it is an indication that the set of requirements is matching the problem domain described in the ontology. This is called *correctness* by Kaiya and Saeki, and the correctness metric is given by:

$$COR = \frac{\text{The number of requirements that maps into the ontology}}{\text{The total number of requirements}}$$

The value of COR should preferably be 1 or as close to 1 as possible.

Completeness (CMP)

Both the description and the definition of the completeness metric appear to contradict the name of the metric, as both indicate an *incompleteness* metric rather than the opposite. This metric is given by:

$$CMP = \frac{\text{The number of ontological elements that have no mappings to the set of requirements}}{\text{The total number of ontological elements}}$$

Note that with the above definition, the value of CMP should preferably be 0 or as close to 0 as possible. The culprit is the word "no" in the numerator, which transforms the definition from completeness to incompleteness. This negation appears to be absent in the earlier paper containing the more mathematical description [36].

In order to illustrate the point further, an example is provided. Assume that there are 5 requirements (the actual number of requirements is actually irrelevant in this example), 10 ontological elements, and that the requirements maps to 8 of the 10 ontological elements. This means that 2 ontological elements remain unmapped. Inserted into the equation, the following result is obtained:

$$CMP = \frac{2}{10} = 20\%$$

A completeness of 20% seems to be a bit low given the numbers in the example. However, an incompleteness of 20% is more reasonable, and by subtracting this value from 1, a completeness of 80% is derived. Of course, if completeness is desirable from the outset, the word "no" could be removed from the definition.

Consistency (CST)

One relationship that may appear in an ontology is that of a *contradiction*. This can be used to mark two concepts as contradictory to each other. If a requirement has mappings to two or more ontological concepts that are connected through a contradiction relation, the requirement is defined as *inconsistent*. The consistency metric is a measure on the opposite, i.e., the lack of contradictory relationships, and is given by:

$$CST = \frac{\begin{array}{l}\text{The number of requirements that are mapped to more than one concept,}\\ \text{of which none of is connected through a contradiction relationship}\end{array}}{\text{The number of requirements that are mapped to more than one concept}}$$

The value of CST should preferably be 1 or as close to 1 as possible.

Unambiguity (UAM)

If a requirement is mapped to two or more concepts that are not connected through relationships, it is here considered *ambiguous*. The *unambiguity metric* is a measure of the opposite, i.e., the lack of such requirements. It is given by:

$$UAM = \frac{\begin{array}{l}\text{The number of requirements that are mapped to concepts}\\ \text{that are connected by one or more relationships}\end{array}}{\text{The total number of requirements}}$$

The value of the UAM should preferably always be equal to 1. It is also possible to produce an *ambiguity metric* by taking $1 - UAM$. In the latter case, the desired value would be 0.

Note that two concepts can be connected through an intermediary concept; it is not necessary that two concepts are connected directly.

Note also that with the above definition of UAM, a requirement which only maps to a single concept will decrease the unambiguity value (and consequently increase the ambiguity value). If this is undesirable, the denominator can be modified to read "The number of requirements that are mapped to more than one concept".

An example: calculating unambiguity

In this example, it is shown how the *unambiguity metric* can be calculated.

The example consists of an ontology with three concepts:

1. fuel level,
2. fuel level gauge, and
3. warning lamp.

Furthermore, there is a relation "display" between the concepts *fuel level gauge* and *fuel level*.

There are also two requirements, where the constituent words "fuel level gauge", "fuel level" and "warning lamp" are mapped to the concepts with identical names in the ontology.

- *EX-1: The fuel level gauge shall display the fuel level.*
- *EX-2: The warning lamp shall be active when fuel level is less than 10% of the tank volume.*

For *EX-1*, there are two mapped concepts, i.e., *fuel level gauge* and *fuel level*. These are connected through the "display" relation previously mentioned. Therefore, *EX-1* will make a contribution to the numerator.

However, for *EX-2*, there is no relationship between the concepts *warning lamp* and *fuel level*. Therefore, *EX-2* will not make a contribution to the numerator. Both *EX-2* and *EX-2* will contribute to the denominator.

This gives the following UAM value:

$$UAM = \frac{\#\{\text{ EX-1 }\}}{\#\{\text{ EX-1, EX-2 }\}} = \frac{1}{2} = 50\%$$

As can be seen above, for small sets of requirements, each requirement in the set will have a large impact on the metrics. In this case, a single requirement contributed to an ambiguity of 50%.

8.4.2 Metrics in DODT

The tool DODT, which was introduced in Chapter 4, use the set of metrics listed in Table 8.1. There are no definitions available on how the metrics are calculated, but they are nevertheless included here in order to provide additional insight into the potential benefits of using ontologies.

The reader should be aware that even though the names of the DODT metrics in some cases are identical to the ones given by Kaiya and Saeki, the definitions are not. For example, the *opacity* metric in DODT appears to have the same definition as $(1 - UAM)$ by Kaiya and Saeki (i.e, the *unambiguity* metric subtracted from 1). This does not mean that either version are more correct than the other, but it is important to be aware of the fact that there are differences.

Table 8.1. *Requirement metrics in DODT. Descriptions quoted verbatim from the DODT user manual [18]*

Metric name	Description
Completeness	The analysis reports all concepts that are linked via relations from requirements concept and that do not occur in the requirements.
Inconsistency	1. Two concepts occurring in the requirements are linked by a contradiction axiom. 2. Two requirements contain identical sets of concepts - in any order and including boilerplate fixed syntax elements and nouns missing from the domain ontology - and exactly one cardinal which is different in the two requirements. For the analysis two concepts linked by an equivalence axiom are considered to be identical.
Ambiguity	It warns about concepts in requirements for which sub-classes exists, i.e., more concrete instances of a concept.
Noise	The noise analysis allows detecting expressions which are not contained in the domain ontology.
Opacity	The opacity analysis allows detecting the usage of unrelated concept in a requirement which possibly means that a concept is used erroneously. The analysis computes if the concepts in a requirement are linked by relations.
Redundancy	The analysis computes if the concepts used in two requirements are identical. For the analysis two concepts linked by an equivalence axiom are considered to be identical.

Part IV:
Case study

9. Case study: CNL with semantics on top

A conclusion from Chapter 8 is that semantic information needs to be included in requirements in order to reduce ambiguity and facilitate computer-aided analysis. In this chapter, the research tool DODT (Domain Ontology Design Tool) is used to demonstrate boilerplates in conjunction with domain ontologies in the context of the *fuel level display* system.

In addition to the demonstration of concepts, a secondary goal is to provide a limited evaluation of DODT, and its potential applicability for Scania. However, this evaluation is by no means full-scale. Indeed, such an evaluation would be of dubious value since DODT is still under development and only exists in very limited availability.

Note that boilerplates do not require a domain ontology or vice versa. It is perfectly possible to use both concepts on its own, and in this case study, boilerplates will not be introduced until step five in the list below, which outlines the steps performed in the study.

1. Creating an ontology.
2. Writing top level requirements in natural language.
3. Analysing the quality of the requirements.
4. Identifying hazards.
5. Refining the requirements into boilerplates.

In a real project, if ISO 26262 was to be followed, step four would be replaced by a more thorough *hazard analysis* and the subsequent specification of SGs (Safety Goal).

9.1 Scenario

For the purpose of the case study, it is assumed that a new *fuel level display* system is to be constructed, and that no prior requirements or documentation exist except for what is described in the *Driver's Manual*. As a resource for getting the nomenclature right, the Scania Lexicon will be used.

In order to proceed, both according to ISO 26262, and also because it is very hard to write requirements otherwise, a definition of the system under work is required. In ISO 26262, this is called the *Item Definition*. In this case study, a definition that is only a part of what ISO 26262 prescribe will be used. To avoid confusion, this limited definition will be called the *system description* and is defined as follows:

The purpose of the fuel level display is to display, in the instrument cluster, the current extractable fuel level from the fuel tank(s) in the vehicle. If the fuel level falls below a certain threshold, a warning indicator in the instrument cluster is activated and then kept active until the fuel level again is above the threshold.

The following components are within the boundary of the system:

- *The fuel level gauge.*
- *The low fuel level warning lamp.*

- ◦ *Any sensors used to measure the fuel level.*
- ◦ *Any cabling connecting the components.*
- ◦ *Any software necessary to process and display the information.*
- ◦ *Any hardware necessary to run the required software.*

9.2 Using DODT

9.2.1 Creating an ontology

To be able to use the analysis capabilities of the DODT tool, an ontology is required. The ontology is represented in OWL. DODT has an built-in editor for creating and editing OWL ontologies, but it is also possible to import and export OWL data files.

For the purpose of the case study, a single ontology was used, but it is also possible to split the ontology into different parts. For example, Farfeleder et al. [20] found it desirable to place non-domain specific measurement units like seconds and kilograms in a separate ontology for reuse in other domains. Another example of a more general ontology is WordNet [41], which contains words and relations from the English language. It is of course also possible to use multiple ontologies internally; this could for example be done at enterprise, division, and product level.

Creating an information model

The first step was to manually review the *Driver's Manual* in order to identify concepts applicable to the stakeholders for the purpose of building an *information model*. Information models are frequently used at Scania to model both system and organisational aspects. In this case, the information model was made as a starting point for the subsequent ontology creation. The information model is depicted in Figure 9.2

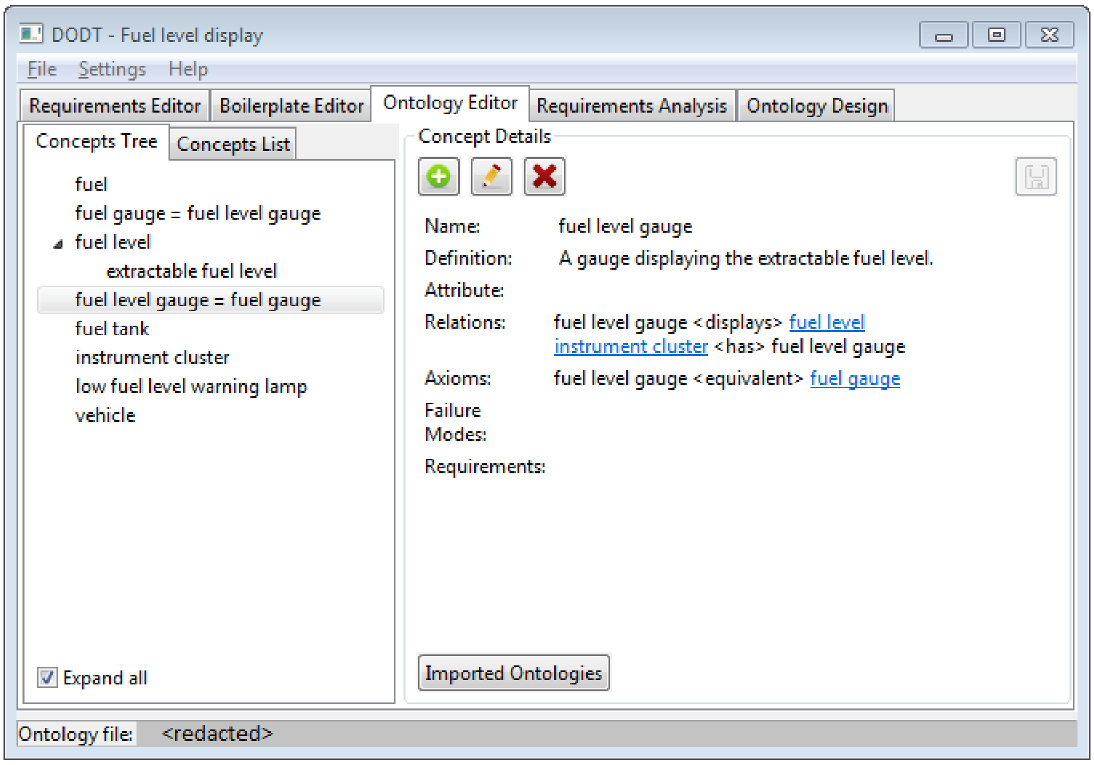
Note that the *fuel level* concept has been refined with a subclass *extractable fuel level* to reflect the domain knowledge that not necessarily all fuel in a tank can be extracted. This a priori knowledge was also stated in the *system description*.

Creating the ontology

The information model was manually translated to an ontology by using the built-in editor in DODT (see Figure 9.1). A UML representation of the initial ontology based on the information model is available in Figure 9.3.

Note that there exist no defined graphical syntax for OWL; the diagram is provided as an illustration for the benefit of the reader rather than a real artefact from the development process. Below is a trimmed portion from the resulting OWL XML file:

```
<owl:Class rdf:about="fuel+gauge">
  <rdfs:label rdf:datatype="string">fuel gauge</rdfs:label>
  <owl:equivalentClass rdf:resource="fuel+level+gauge"/>
  <rdfs:subClassOf rdf:resource="system"/>
  <system-attributes:deprecated rdf:datatype="string">1</system-attributes:deprecated>
  <rdfs:comment rdf:datatype="string">Deprecated synonym</rdfs:comment>
</owl:Class>
```



fuel
fuel gauge = fuel level gauge
fuel level
extractable fuel level
fuel level gauge = fuel gauge
fuel tank
instrument cluster
low fuel level warning lamp
vehicle

Name: fuel level gauge
Definition: A gauge displaying the extractable fuel level.
Attribute:
Relations: fuel level gauge <displays> fuel level
instrument cluster <has> fuel level gauge
Axioms: fuel level gauge <equivalent> fuel gauge
Failure Modes:
Requirements:

Ontology file: <redacted>

Figure 9.1. The *Ontology Editor* feature in DODT.

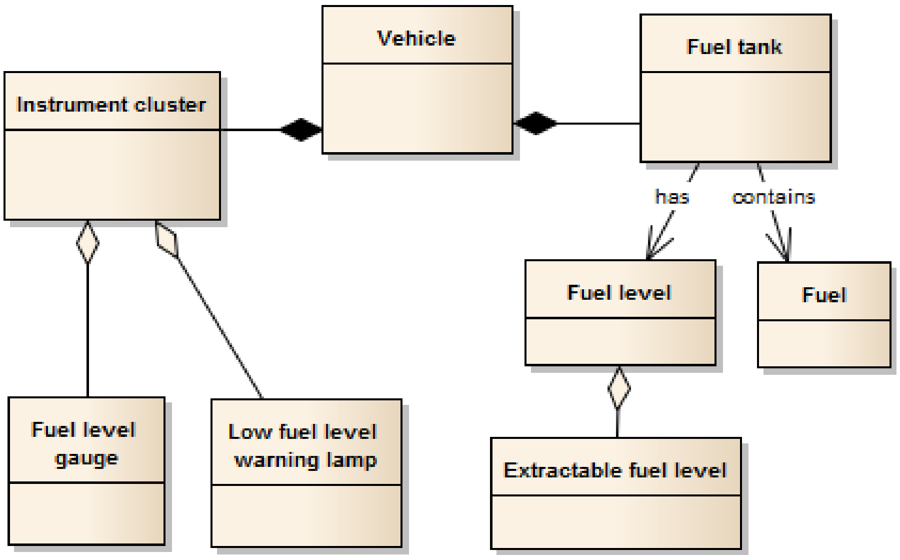
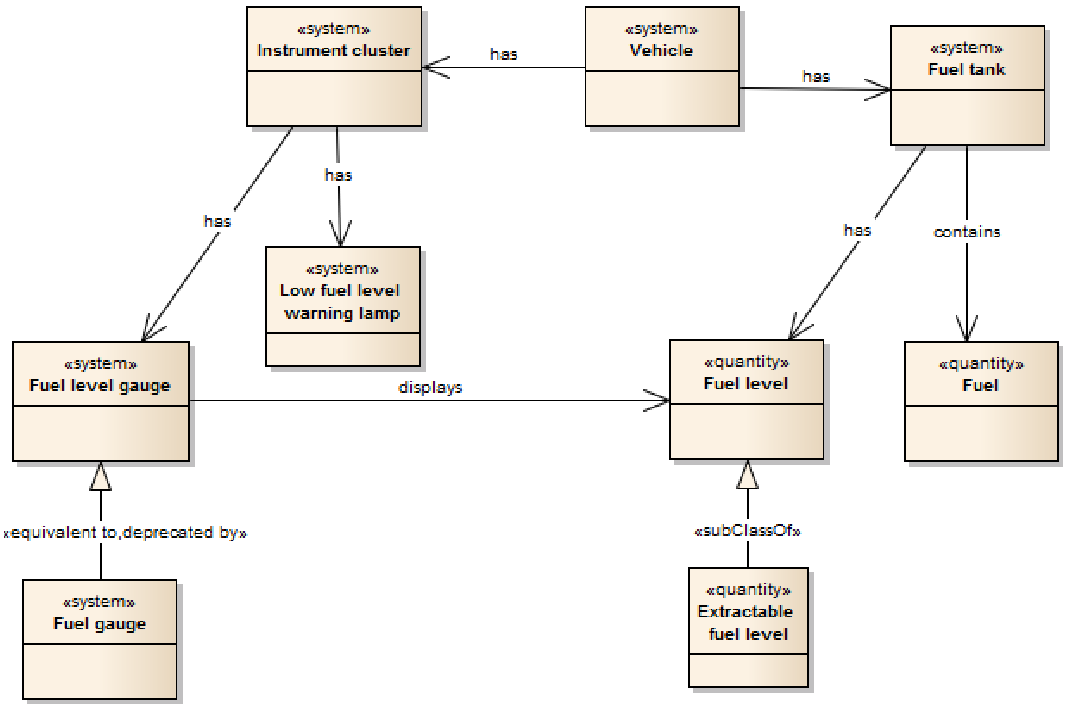


Figure 9.2. An information model for the *Fuel level display*, which was used as inspiration when creating the ontology.



«system» Instrument cluster
has
«system» Vehicle
has
«system» Fuel tank
has
has
«system» Low fuel level warning lamp
has
contains
«system» Fuel level gauge
displays
«quantity» Fuel level
«quantity» Fuel
«equivalent to,deprecated by»
«subClassOf»
«system» Fuel gauge
«quantity» Extractable fuel level

Figure 9.3. Ontology represented as UML diagram. Note particularly the “deprected by, equivalent to” axiom between the *Fuel level gauge* and *Fuel gauge* concepts.

Information model versus ontology

As already mentioned, the information model was used as a starting point; the mapping between the information model and the concepts in the ontology is therefore not one-to-one. Some noteworthy differences in the ontology as compared to the information model are that:

- The concept *fuel level gauge* from the *Driver's Manual* is labelled *fuel gauge* in the Scania Lexicon. To improve consistency, the latter is defined (in DODT) as an obsolete synonym. It is of course possible to reverse this relation and make the *fuel level gauge* the deprecated version. Note that in the Scania Lexicon as well as in OWL, the word *deprecated* is used instead of *obsolete*. For the remainder of this chapter, *deprecated* will be used.
- Additional relations have been added: for example, the concept *fuel level gauge* has a relation <*display*> with the concept *fuel level*.
- Attribute types have been added to all concepts, as these are used by DODT to suggest suitable completions when writing the requirements. In this case study, only the attributes *system* and *quantity* were used.

9.2.2 Writing requirements in natural language

When a requirement is being formulated in natural language, DODT uses the ontology to suggest suitable concepts and relations. This is illustrated in Figure 9.4. Provided that the mental picture of the user corresponds to that of the ontology, it becomes easier to use well-defined concepts than to use or invent synonyms. Since the tool is able to suggest parts of sentences longer than a single word, the time to write a requirement can be reduced.

Note particularly that when a suggestion is marked in the tool, DODT displays the description of the associated concept. This helps the users to ensure that they are using the right concepts.

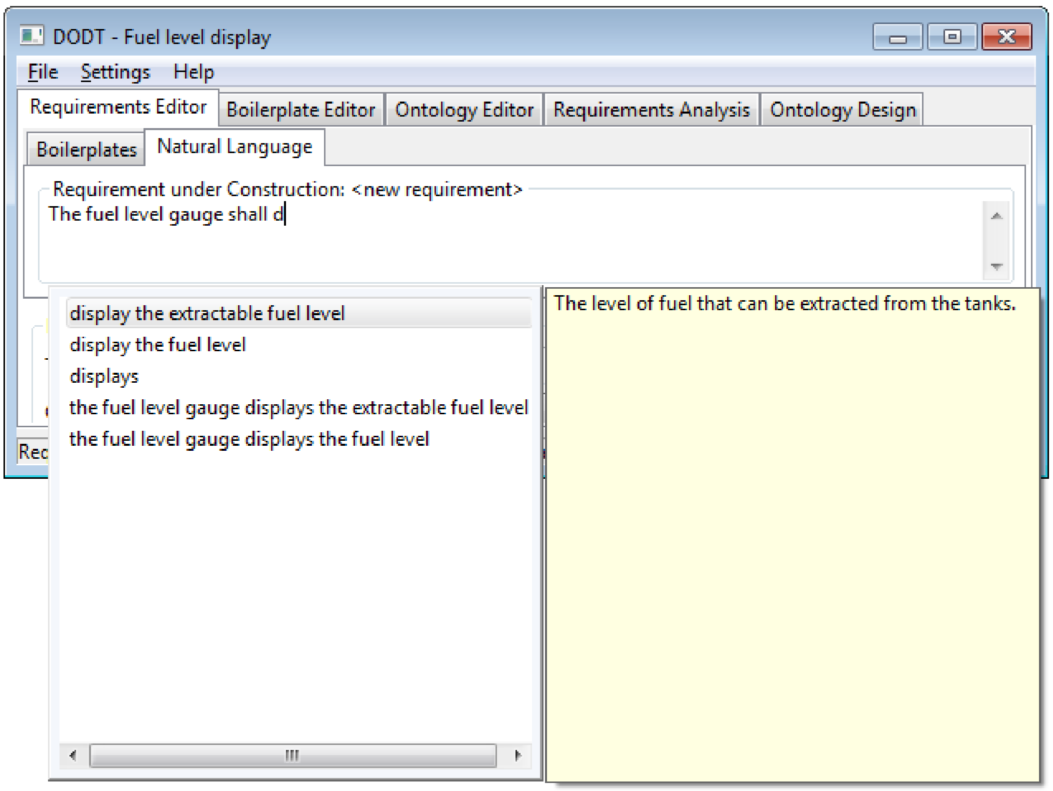
If an attempt is made to use a deprecated term, DODT gives a warning and propose a change to the preferred alternative before saving the requirement. This is illustrated in Figure 9.5.

In DODT, a requirement has both a category and a type. The predefined categories are *Functional*, *Non-Functional* and *Safety*. The predefined types are *Requirement*, *Goal* and *Assumption*. This makes it possible to keep track of safety-related requirements, and to separate goals from lower level requirements. Both categories and types can be modified by the user.

Two top level requirements together with two assumptions were deemed sufficient to capture the essence of the *system description*. The requirements and assumptions are listed in Table 9.1

Table 9.1. *Top level requirements for the fuel level display*

ID	Requirement text
REQ0	The fuel level gauge shall display the extractable fuel level.
REQ1	The low fuel level warning lamp shall be active when the extractable fuel level is less than a specified threshold.
ASN0	The fuel level gauge shall be placed in the instrument cluster.
ASN1	The low fuel level warning lamp shall be located in the instrument cluster.


DODT - Fuel level display

Requirement under Construction: <new requirement>

The fuel level gauge shall d

display the extractable fuel level

display the fuel level

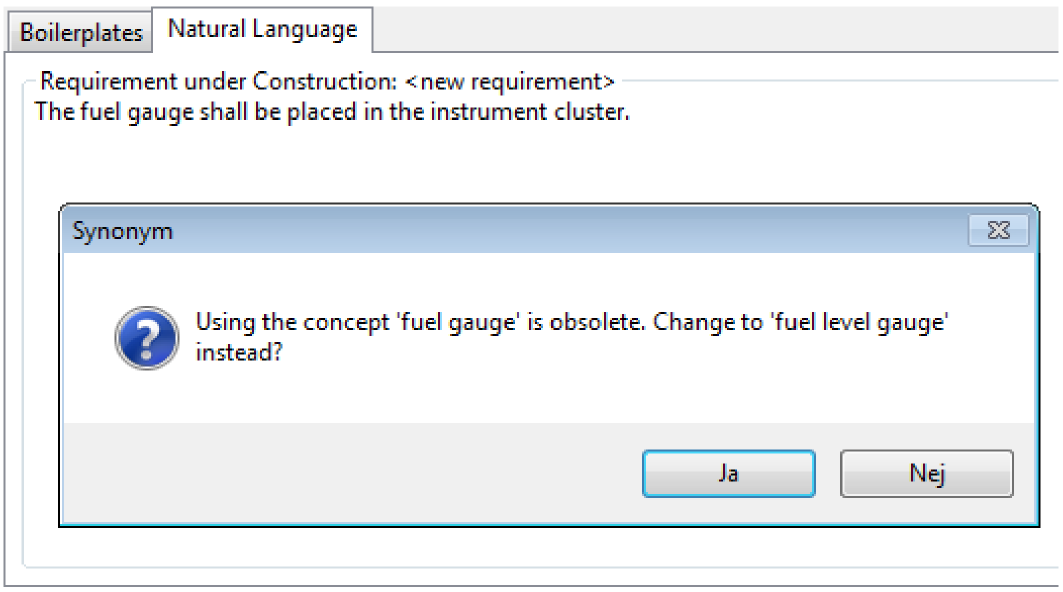
displays

the fuel level gauge displays the extractable fuel level

the fuel level gauge displays the fuel level

The level of fuel that can be extracted from the tanks.

Figure 9.4. A requirement being written in natural language.



Requirement under Construction: <new requirement>

The fuel gauge shall be placed in the instrument cluster.

Synonym

Using the concept 'fuel gauge' is obsolete. Change to 'fuel level gauge' instead?

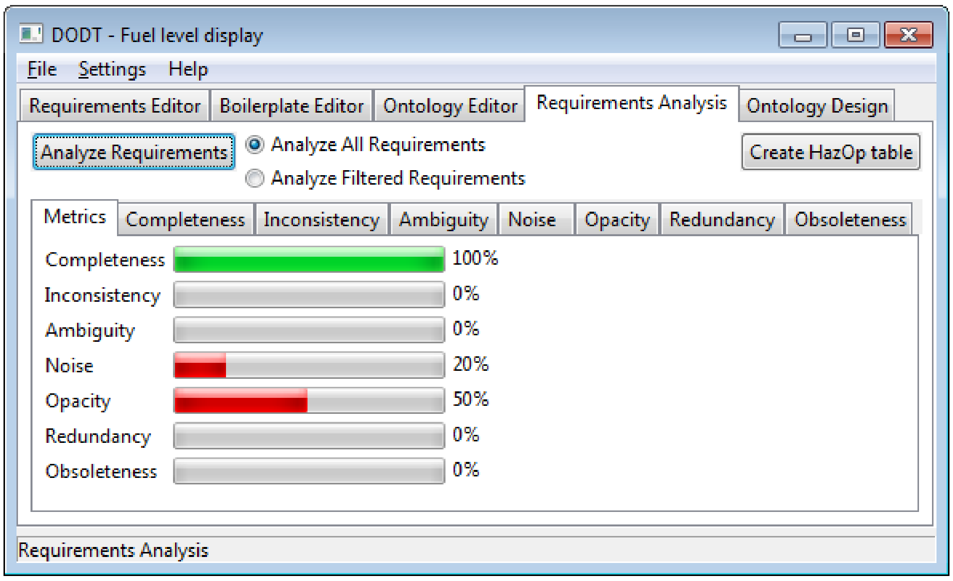
Figure 9.5. Dealing with a deprecated concept.

Note that in the assumptions (*ASN0* and *ASN1*) above , the words “placed” and “located” have similar, if not identical semantics. Also, in *REQ1*, “when” is used instead of “while”. The word “when” is of a discrete nature whereas “while” is continuous and therefore more suitable in this occasion. These “mistakes” were deliberate in order to test the capabilities of the tool; this will be explained further in a latter section.

9.2.3 Analysing the quality of the requirements

After the requirements have been specified, the analysis feature of DODT can be used to calculate requirement metrics. The metrics were described in Chapter 8, where it also was explained that constituent words in the requirements must to be mapped to concepts or relations in the ontology. This mapping is done automatically by DODT. Figure 9.6 shows the result. By switching to the different tabs in DODT, detailed information regarding the identified problems can be seen. In this particular case, both *noise* and *opacity* were detected.

By right-clicking on each warning, DODT offers shortcuts for either adding the missing concept or revising the offending requirement. If the analysis is done with an empty ontology, 100% noise is detected.



Completeness	100%
Inconsistency	0%
Ambiguity	0%
Noise	20%
Opacity	50%
Redundancy	0%
Obsoleteness	0%

Figure 9.6. Requirements analysis in DODT.

Noise

Noise indicates the presence of one or more concepts in a requirement with no corresponding entries in the ontology. DODT identified the following noise:

Table 9.2. *Requirements analysis: identified noise*

ID	Output from DODT
REQ1	*Noisy concept: 'threshold'*

The warning for *REQ1* was solved by adding a new concept *low fuel level threshold* in the ontology and making a corresponding change to the requirement. The two versions of *REQ1* is shown in Table 9.3.

Table 9.3. *Modification of* REQ1 *– the difference marked with emphasis*

Version	Text
OLD	The low fuel level warning lamp shall be active when the extractable fuel level is less than a specified threshold.
NEW	The low fuel level warning lamp shall be active when the extractable fuel level is less than *the low fuel threshold.*

In the Noise tab in DODT, it is possible to mark a checkbox titled "Ignore nouns known to WordNet". Checking that box would also make the noise warning to disappear since the word "threshold" indeed exist in WordNet. However, the aim of this thesis is to reduce ambiguity, so it was preferred to instead add a a concept to the ontology. Doing so allows for a domain specific definition of the complete concept "low fuel level threshold" rather than the more general WordNet definition of the word "threshold".

Opacity

In DODT *opacity* means that two unrelated concepts are used in the same requirement.

It is interesting to note that the actions performed to remove the noise also increased the opacity from 50% to 60%, giving the following output (the increased opacity is due to the second warning related to *REQ1*):

Table 9.4. *Requirements analysis: identified opacity*

ID	Output from DODT
REQ1	*Unrelated concepts 'low fuel level warning lamp' and 'extractable fuel level'*
REQ1	*Unrelated concepts 'low fuel level warning lamp' and 'low fuel level threshold'*

The reason was that DODT was unable to find relations between the concepts listed in the warnings. The solution was to:

a) make the *low fuel level threshold* a subclass (specialisation) of *fuel level*. This can be motivated because *low fuel level threshold* can be seen as one of several possible fuel levels in a tank.

b) create a relation between *low fuel level warning lamp* and *low fuel level threshold*, so that "low fuel level warning lamp <activates on> low fuel level threshold".

It is important to note that *a)* not in itself will remove the first warning unless *b)* also is performed. The oposite is not true however; by doing *b)* the second warning disappears independently of whether *a)* is performed or not. To better understand why this is so, refer to Figure 9.9 and mentally remove the link titled "activates on".

9.2.4 Identifying hazards

One interesting and promising feature in DODT is its ability to create an Excel file containing a template for hazard identification. The spreadsheet can then, for example, be used as input for the hazard analysis prescribed by ISO 26262. To be able to use this feature, *failure modes* must first be defined for relevant concepts.

In order to test both this feature and the ontology technique further, the failure modes were not associated directly to the existing concepts where the failures would be observed, i.e., the *fuel level gauge* and the *low fuel level warning lamp*; instead, two more general concepts were introduced into the ontology, for which the failure modes then were added. The two new concepts were:

a) *gauge*, which the *fuel level gauge* was made a subclass of, and

b) *warning lamp*, which the *low fuel level warning lamp* was made a subclass of.

The advantage of adding failure modes for more general concepts is that those will be inherited and therefore do not have to be specified anew every time some sort of warning lamp is added to the ontology. The failure modes of a warning lamp is quite static, and if for some reason an additional failure mode is relevant for a more specialised concept, it can be added specifically to it.

When defining a failure mode for a concept in DODT, a *guideword* must be chosen. The available guidewords are "omission", "comission" and "stuck". Guidewords are also called *failure classes*, e.g., by Johannessen et al. [34].

Johannessen et al. use the guideword "omission" when an actuator does not react on intent from a driver (e.g., by pressing a brake pedal), "comission" when it activates without intent (i.e., incorrectly), and "stuck" when the actuator becomes mechanically locked. They also argue that while there are other guidewords such as "late", there is little difference from "omission", and that "omission" furthermore can be seen as the worst case of "late".

In any case, DODT only allows the three guidewords stated above, so they have to be used in the fuel level display example. If the warning lamp is considered an actuator, and the fuel level display system is ascribed intent to activate the lamp at the right time, then a too late activation can be classified as an "omission" and a too early (i.e., incorrect) activation as a "commission".

For the fuel level gauge, it can be assumed that the fuel level gauge takes a continuous voltage as input, and that this voltage is directly translated to a value on the gauge. It can be further assumed that a higher voltage means a higher remaining volume and therefore a higher value on the gauge. By these assumptions, a too high value can be seen as a"commission" (incorrect activity), while a too low value can be seen as an "omission" (lack of activity).

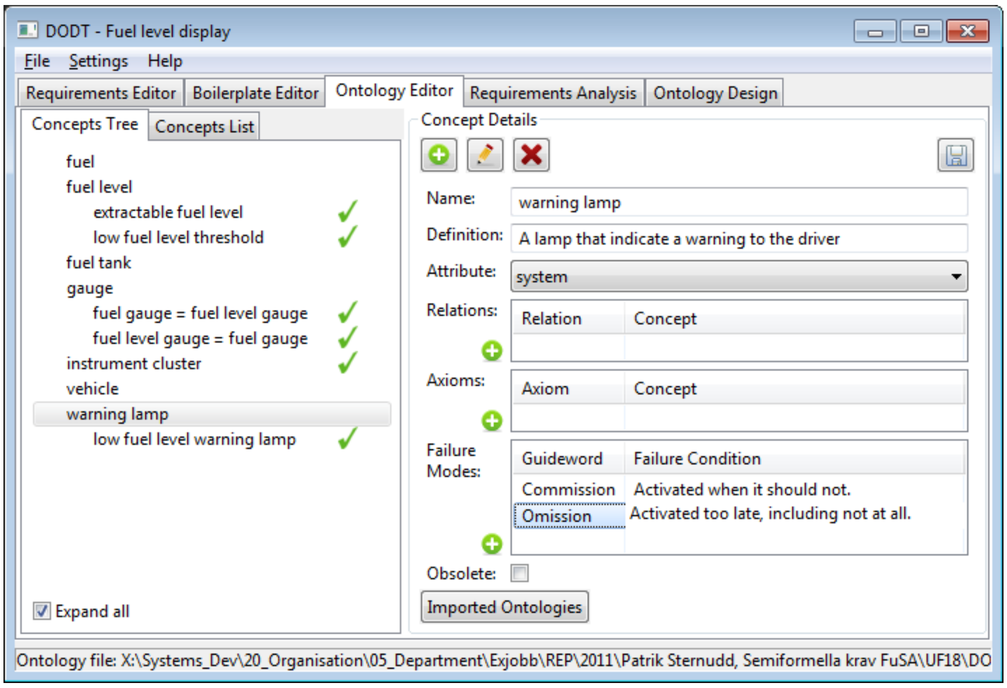
Note, however, that the above assumptions only may hold for certain types of fuel level gauges. The reasoning was performed in order to derive a suitable guideword; no claims are made for fuel level gauges in general.

Table 9.5 shows the failure modes that were added to the concepts, and Figure 9.7 depicts the *warning lamp* concept in DODT.

Table 9.5. *Failure modes added to concepts in the ontology*

Concept	Guideword	Failure mode
Warning lamp	Omission	Activatd too late, including not at all.
Warning lamp	Comission	Activated when it should not.
Gauge	Omission	Shows a too low value.
Gauge	Comission	Shows a too high value.

After the failure modes had been added, DODT was asked to output the Excel spreadsheet. This can be done in *Requirements analysis* screen (see Figure 9.6). The resulting output is shown in Figure 9.8. As can be seen, it is not a complete hazard analysis; the system architects must still consider the effects of a particular failure, but by using the feature, they get assistance in generating an initial spreadsheet.



fuel
fuel level
  extractable fuel level ✓
  low fuel level threshold ✓
fuel tank
gauge
  fuel gauge = fuel level gauge ✓
  fuel level gauge = fuel gauge ✓
instrument cluster ✓
vehicle
warning lamp
  low fuel level warning lamp ✓

[✓] Expand all

Name: warning lamp
Definition: A lamp that indicate a warning to the driver
Attribute: system

Relations:

Relation	Concept

Axioms:

Axiom	Concept

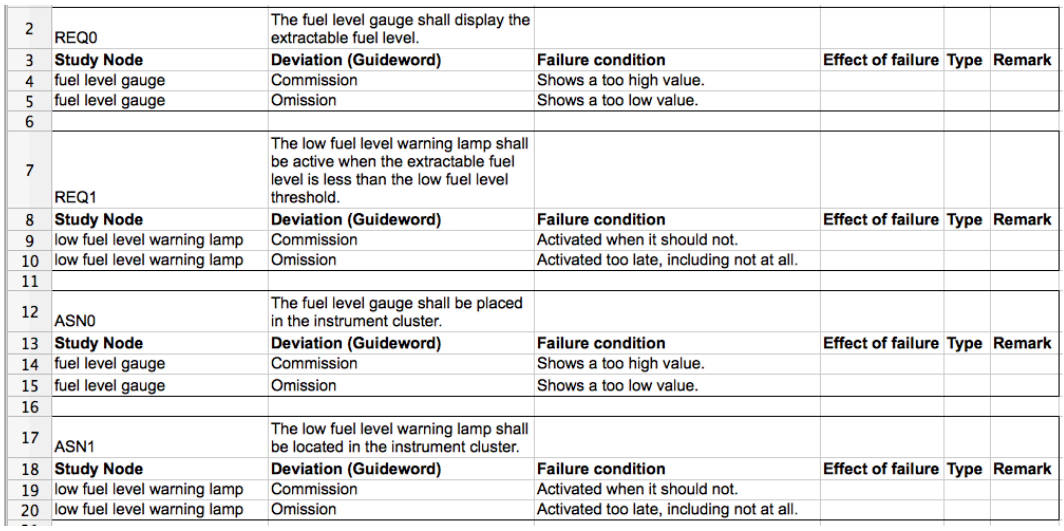
Failure Modes:

Guideword	Failure Condition
Commission	Activated when it should not.
Omission	Activated too late, including not at all.

Obsolete: [ ]

Ontology file: X:\Systems_Dev\20_Organisation\05_Department\Exjobb\REP\2011\Patrik Sternudd, Semiformella krav FuSA\UF18\DO

Figure 9.7. Ontology concept with failure modes.



2	REQ0	The fuel level gauge shall display the extractable fuel level.				
3	**Study Node**	**Deviation (Guideword)**	**Failure condition**	**Effect of failure**	**Type**	**Remark**
4	fuel level gauge	Commission	Shows a too high value.			
5	fuel level gauge	Omission	Shows a too low value.			
6						
7	REQ1	The low fuel level warning lamp shall be active when the extractable fuel level is less than the low fuel level threshold.				
8	**Study Node**	**Deviation (Guideword)**	**Failure condition**	**Effect of failure**	**Type**	**Remark**
9	low fuel level warning lamp	Commission	Activated when it should not.			
10	low fuel level warning lamp	Omission	Activated too late, including not at all.			
11						
12	ASN0	The fuel level gauge shall be placed in the instrument cluster.				
13	**Study Node**	**Deviation (Guideword)**	**Failure condition**	**Effect of failure**	**Type**	**Remark**
14	fuel level gauge	Commission	Shows a too high value.			
15	fuel level gauge	Omission	Shows a too low value.			
16						
17	ASN1	The low fuel level warning lamp shall be located in the instrument cluster.				
18	**Study Node**	**Deviation (Guideword)**	**Failure condition**	**Effect of failure**	**Type**	**Remark**
19	low fuel level warning lamp	Commission	Activated when it should not.			
20	low fuel level warning lamp	Omission	Activated too late, including not at all.			

Figure 9.8. Potential failures in the fuel level display identified by DODT.

9.2.5 Requirements and ontology after analysis

The complete set of requirements is shown in Table 9.6. The only change from the initial set is the refinement of *low fuel level threshold* in *REQ1*.

Table 9.6. *Changes to requirements after analysis feedback*

ID	Requirement text
REQ0	The fuel level gauge shall display the extractable fuel level.
REQ1	The low fuel level warning lamp shall be active when the extractable fuel level is less than the low fuel level threshold.
ASN0	The fuel level gauge shall be placed in the instrument cluster.
ASN1	The low fuel level warning lamp shall be located in the instrument cluster.

The final version of the ontology after refinement during the process is depicted in Figure 9.9

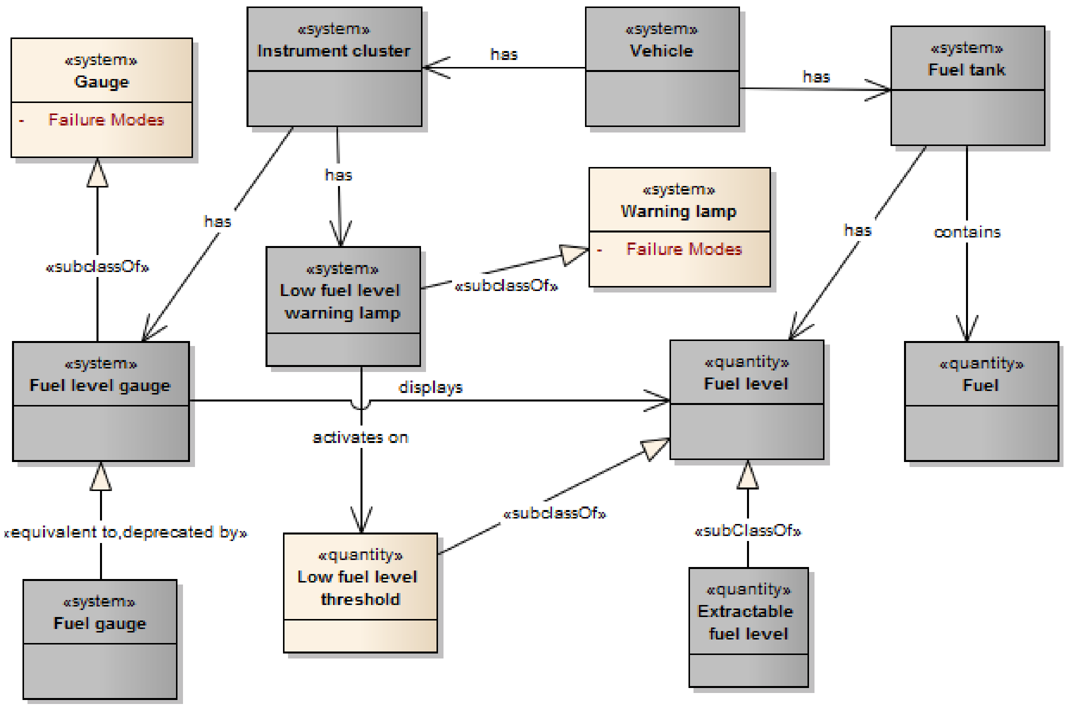


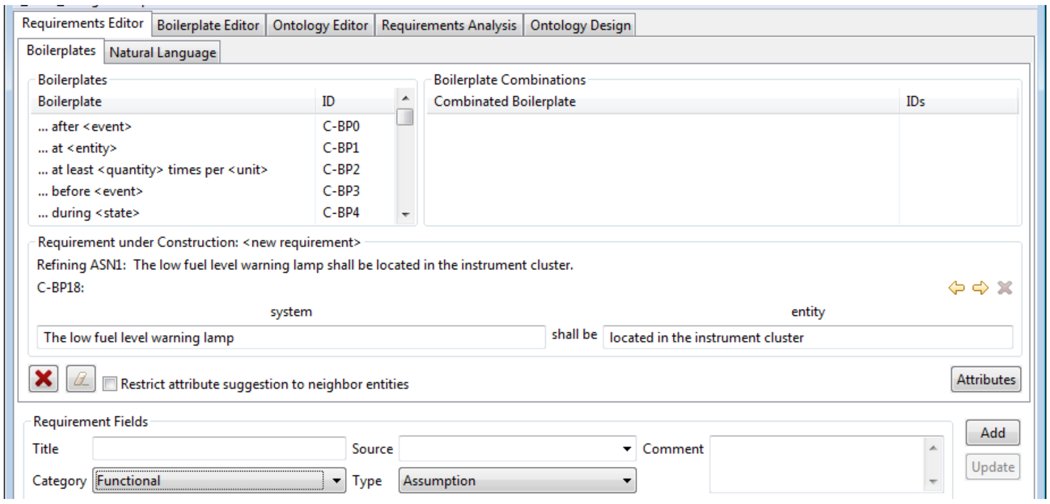
Figure 9.9. Ontology after refinement. Unchanged elements have a darker colour.

9.2.6 Refining the requirements into boilerplates

In this step, the previously created requirements that were written in natural language were refined into boilerplate requirements.

In order to use the boilerplate feature, a set of boilerplates must first be defined in DODT. This can either be done by the built-in *Boilerplate Editor*, by importing a XML file, or by using an existing set from the CESAR Project. The CESAR set shipped with the version used for the demonstration contains 31 different boilerplates.

When a natural language requirement is chosen for refinement, DODT use a natural language parser to select a suitable boilerplate. Multiple boilerplates can also be combined in order to better fit the requirement text. If more than one candidate boilerplate (or boilerplate combination) are found, the user is presented with a list to choose from. After the boilerplate has been selected, the attribute portions are prefilled from the requirement, and the user can, if applicable, change both the text and the choice of boilerplates. This is illustrated in Figure 9.10.



Boilerplates

Boilerplate	ID
... after <event>	C-BP0
... at <entity>	C-BP1
... at least <quantity> times per <unit>	C-BP2
... before <event>	C-BP3
... during <state>	C-BP4

Boilerplate Combinations

Combinated Boilerplate	IDs

Requirement under Construction: <new requirement>
Refining ASN1: The low fuel level warning lamp shall be located in the instrument cluster.
C-BP18:

system		entity
The low fuel level warning lamp	shall be	located in the instrument cluster

Restrict attribute suggestion to neighbor entities

Requirement Fields

Title		Source		Comment	
Category	Functional	Type	Assumption		

Figure 9.10. Refining the natural language assumption *ASN1* into boilerplate form. DODT has automatically chosen the boilerplate *C-BP18*, but additional ones can be selected from the top-left corner. The yellow arrows to the right (directly above the requirement) can be used to reorder or delete selected boilerplates.

The CESAR boilerplate set

In this step, the set of boilerplates from the CESAR Project was used to refine the requirements. Only boilerplates suggested by the tool were used; no manual selection was performed unless DODT presented more than one candidate, in which case the boilerplate with the most amount of fixed syntax was chosen. The list of used boilerplates is shown in Figure 9.8. The result is shown in Table 9.7.

Table 9.7. *Requirements in boilerplate form, using the CESAR Project set of boilerplates. Attributes are placed within <>, and ontology concepts are emphasised.*

ID	Requirement	BPs
REQ0	<The *fuel level gauge*> shall <display the *extractable fuel level*>	C-BP16
REQ1	<The *low fuel level warning lamp*> shall be <active when the *extractable fuel level* is less than the *low fuel level threshold*>	C-BP18
ASN0	<The *fuel level gauge*> shall be <placed in the *instrument cluster*>	C-BP18
ASN1	<The *low fuel level warning lamp*> shall be <located in the *instrument cluster*>	C-BP18

Table 9.8. *Definition of CESAR boilerplates listed in Table 9.7*

ID	Boilerplate form
C-BP16	*<system> shall <action>*
C-BP18	*<system> shall be <entity>*

Tailor-made boilerplates

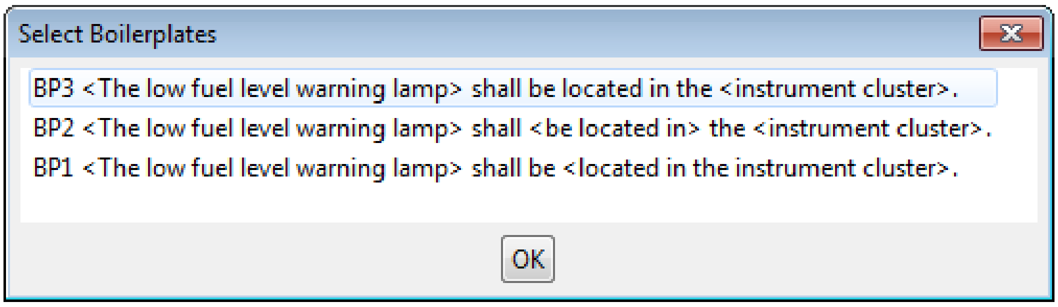
In order to get a larger part of the syntax fixed, custom boilerplates for the fuel level display were created. The motivation for desiring a large fixed part was to achieve a semi-formal syntax as per the ISO 26262 definition. A more constrained syntax may also make it easier to attach meanings to the fixed syntax elements in order to perform automatic analysis or translation.

During the boilerplate creation, the ambition was to keep them as general as possible in order to avoid getting a specific boilerplate for each future requirement. The following boilerplates were sufficient for the initial requirements:

Table 9.9. *Custom boilerplates created for the fuel level display*

ID	Boilerplate form
BP1	*<system> shall be <state>*
BP2	*<system> shall <action> <entity>*
BP3	*<system> shall be located in <entity>*
BP4	*. . . while <quantity> is less <quantity>*

When refining the original requirements using the custom boilerplates, DODT was able to suggest better matches than with the CESAR set. Figure 9.11 shows an example of this. The final result can be seen in Table 9.10.


Select Boilerplates

BP3 <The low fuel level warning lamp> shall be located in the <instrument cluster>.
BP2 <The low fuel level warning lamp> shall <be located in> the <instrument cluster>.
BP1 <The low fuel level warning lamp> shall be <located in the instrument cluster>.

Figure 9.11. Refinement from NL to custom boilerplates.

Table 9.10. *Requirements in boilerplate form, using a custom set of boilerplates. Attributes are placed within <>, and ontology concepts are emphasised.*

ID	Requirement	BPs
REQ0	<The *fuel level gauge*> shall <display> <the *extractable fuel level*>	BP2
REQ1	<The *low fuel level warning lamp*> shall be <active> while <the *extractable fuel level*> is less than <the *low fuel level threshold*>	BP1+BP4
ASN0	<The *fuel level gauge*> shall be located in <the *instrument cluster*>	BP3
ASN1	<The *low fuel level warning lamp*> shall be located in <the *instrument cluster*>	BP3

However, the matching is highly dependent on the actual wording of the requirements. For example, in the natural language version *REQ1*, the word "when" was used instead of "while", which made DODT to suggest a more general boilerplate (BP2). Changing the wording in the requirement to "while" made DODT to choose the better matching BP1 + BP4 directly.

In the same manner, DODT was able to suggest the best match for *ASN1* (BP4), but not for *ASN0*. The only structural difference between them are that in the latter case, the word "placed" was used instead of "located". Of course, by using the boilerplates, it may be easier for the user to realise that there is a better boilerplate and thus change the wording either in the requirement or during refinement, but the best would be if DODT could be made aware of the fact that "located" and "placed" are synonyms and therefore suggest the better matching boilerplate. Similarly, the tool could be aware that, while not strictly synonyms, "while" could be an alternative to "when".

It can be argued that the above discussion only has academic value, and that, in a real case, it would have been spotted right away during the specification of the natural language requirements. This may be so, and definitely if the two requirements are listed adjacent to each other, but in practice, it is also quite possible that there are more than four requirements for a complete system. There is then a risk that those two requirements would have several other requirements in between. If the different wording would not be found and corrected, it could lead to confusion by readers who might wonder if they are different for a reason. By using the same fixed syntax in the boilerplate, this is avoided.

Another solution is to change the ontology relations between the concepts "instrument cluster", "gauge" and "warning lamp". For example, instead of the relation "has" which was derived from the initial information model, a more specific relation "located in" could be used. Although this does not affect the boilerplate selection, guidance is provided at the time of writing the requirement. However, the requirements analysis does not flag that the word "placed" is used instead of "located". Neither the analysis or the boilerplate selection seems to factor in the name of the relations, only the fact that there *is* a relation seems to matter. There are also no way to specify a synonym to a relation in DODT. This could be a future improvement of the tool.

The previous paragraph also begets the question on how similar the ontology and the requirements should be. This question is discussed in more detail in the next section.

9.3 Evaluation

In this section, an evaluation of the above case study is presented. It will focus more on the concepts of domain ontologies and boilerplates rather than the tool DODT itself. It is however worth to mention that DODT as a tool is quite user-friendly and easy to work with. For example, it is easy to reach relevant features without using the main menu. The user-friendliness of any requirements tool is likely to be a key success factor for its acceptance among the user base.

There is also a potential psychological factor relating to the requirements analysis feature. As the feedback from the tool is available directly, users may use it to challenge themselves to write good requirements, which of course would affect the quality in a positive way.

One feature that is under development in DODT and therefore could not be tested is the automatic generation of an ontology by using a document as input. This feature can potentially simplify the ontology creation, but is likely to require some experience with ontologies in order add or remove concepts or relations after the generation process.

It should be noted that the case study only was done on a very small number of requirements, so it is impossible to draw any conclusions on the scalability or behaviour of a larger system, or even the same system at a more technical level with more requirements.

9.3.1 Ontology quality

The success of the tool and indeed the technique itself is highly dependent on the quality of the ontology. If important concepts are missing, the guidance and analysis will suffer. If the relations or axioms between the concepts are suboptimal, the user is likely to be distracted by suggestions that do not make sense. Additionally, if the ontology also is used for the purpose of conveying a common vocabulary, it becomes even more important to ensure the quality of the contents. Therefore, any shared ontology should be centrally managed and new entries carefully reviewed before being entered into the ontology.

On the other hand, it seems likely that new concepts and relations will be identified during the requirements specification. To avoid delays during the specification, it should be easy for the users to add missing entries. However, if the users are not familiar with the ontology technique, they might include entries that are not optimal, which would degrade the quality. Therefore, a balance between ease of use and quality control is needed for ontologies that is used by more than one person.

9.3.2 Ontology versus requirements

One observation from the case study is that the closer the names of the relations in the ontology are to the real world, the better is the guidance provided by DODT during requirements formulation. Also, if there are no relations between two concepts that are used in the same requirement, this will be identified as opacity when using the requirements analysis feature. The only way to make the opacity warnings disappear is to add a relation between the concepts, either directly or indirectly (e.g., to a higher-level concept). Additionally, if the requirements do not make use of the concepts in the ontology, the requirements analysis feature will lose its usefulness as every identified concept will be flagged as noise.

However, if the ontology technique works best when both its concepts and relations matches the requirements, then what is the difference between the requirements and the ontology? Cannot the ontology replace the requirements altogether?

First, it should be pointed out that in this thesis, the purpose using the technique is to facilitate the production of natural language-like requirements with low ambiguity. In fact, the creation of the ontology could be seen as nothing more than an intermediary step in the process of writing the requirements, much as an information model can be used to create an abstraction of the reality. Indeed, if the ontology only is used by a single person and not shared within the organisation, this would be quite close to the truth. However, the technique will be even more powerful if a shared ontology is used, because it would lead to a common vocabulary and also the possibility to find conflicts between requirements in different systems.

Secondly, if the ontology contains concepts and relations that are shared through the organisation (e.g., derived form the *Driver's Manual*), the contents should not be more specific than what all stakeholders can agree is useful. The actual requirements can however be more specific without affecting the ontological elements. For example, during the more technical design phase of the fuel level display, *REQ1* could be refined into:

> *The low fuel level warning lamp shall be activated when the extractable fuel level has been less than 10% of the total tank volume for a time period exceeding 30 seconds.*

While concepts such as "total tank volume" and possibly also "time period" and "seconds" might need to be included in the ontology if they not already exist, there is no point in adding the actual values (10% and 30 seconds).

It may also be interesting to compare the ontology with a formal specification (see Chapter 7). For formal specifications, it is recommended that natural language versions accompanies the formal requirements, but that the formal version has precedence. In the case of ontologies, it is the other way around. The ontology, together with the tool DODT, is used to produce the actual natural language requirements. The resulting requirements can then be placed under change management and validated by the stakeholders.

In some sense, the ontology can be seen as a modelling tool for high-level requirements in the problem domain. This may be a suitable viewpoint, because it would make the most out of the technique in terms of guidance during specification and requirements analysis. It would of course have to be made explicit within the organisation that the ontology is a model and that the actual requirements used for system development are stored elsewhere.

By using the above reasoning, the previously posed question regarding the relationship between the concepts *instrument cluster* and *fuel level gauge* can be answered. It should be the more specific "located in" rather than the original "has", which was taken directly from the information model. It should be pointed out that the "has" relationship appears to be quite common in information models; this would be something to keep in mind when deriving ontology relations from that type of sources.

Finally, there is another aspect that must be discussed. If a natural language requirement is the output from the process, what about the concept description available in the ontology? Should that information be part of the requirement or not? This question can be further extended: *Which information should be specified in the requirements, which information should exist in the ontology, and finally, what should not specified at all because it is "common knowledge"?*. This question is equally relevant when there is no ontology but instead only a glossary.

From an ambiguity point of view, the term "common knowledge" above should raise a warning flag, because that is just the kind of assumption that comes back to haunt projects later on. On the other hand, the line must be drawn somewhere; at some point the value of writing detailed definitions disappears. The question is where that point is. For example, is it necessary to define what the word "colour" actually means?

To decide whether to place information in the requirements or in the ontology is perhaps even harder. A requirement that is short and concise is easier to understand, but if that is achieved by omitting certain information such as implicit assumptions, there is a high risk of ambiguity. Compare the following three versions of the same requirement:

a) "The fuel level gauge shall display the extractable fuel level to the driver."

b) "The fuel level gauge shall display the extractable fuel level."

c) "The fuel level gauge shall display the fuel level."

Alternatives b) and c) do not state to whom or what the fuel level is supposed to be displayed to, while alternative a) makes it explicit. Can it be assumed that it is always the driver? Not necessarily - it depends on the interpretation of the word "display". Since it is dangerous to make assumptions regarding interpretations, it would then be a good idea to have a clear definition of the word "display" in the ontology or glossary.

Alternative c) furthermore omits the word "extractable". Possibly, it could be clarified in a glossary or an ontology that "fuel level" actually means "extractable fuel level", but this may not be an option if other types of fuel level must be referred to, e.g., "measured fuel level". In some occasions, the actual fuel level may be of interest as well, e.g., due to fire concerns.

Although a requirement statement can be made more concise by moving definitions to a glossary, it places greater demand on the reader to actually refer to the glossary. Additionally, it should somehow be made obvious that a certain word have an external description. There is also a risk that a reader will refrain from referring to the glossary because they thinks that the meaning is obvious, thus leading to misunderstandings. This can be somewhat mitigated with tools like DODT as the concept description is displayed when the requirement is written. In any case, it would be good practice to discuss the requirements formulations together with the glossary definitions during the requirements validation step.

More problematic is the fact that what actually happens when clarifying words are extracted and placed in a glossary or an ontology is that the requirement itself is extended to an external source. This means that the need for change management is extended to that source, as it must be possible to relate a particular version of a requirement with the particular description that was current at the time of specification.

However, a simpler solution may be to extract the description and store it together with the accepted requirement. On the other hand, if this is done, another question arise: should the stored version be used when the requirement is modified, or should the current description from the ontology be retrieved?

Unfortunately, even with adequate change management in place, it can be dangerous if there exist multiple versions of a description, because the users of the requirements would have to keep different interpretations of the same concept in their minds at the same time.

One way to avoid or at least reduce the problem is to have a strict quality control which ensures that only descriptions and entries that there already are commonly established in the organisation are included, and that only minor changes that do not change the actual meaning are performed afterwards. This is of course easier said than done.

9.3.3 Boilerplates

If requirements are to be written in boilerplate form, it is important to have a set of boilerplates with as few elements as possible while still allowing the engineer to express domain specific requirements in it. If the set is too large, there is a risk of too disparate formulations. If it is too small, the quality of the requirements may be affected because important information is left out because it does not fit into the templates.

It will therefore be necessary to spend some time developing a suitable set of boilerplates. It is also possible that different sets will be needed for different departments. The users who would ultimately use such a tool are likely to need some training before starting using it. This sentiment is also shared by Farfeleder et al. :

> The selection of suitable boilerplates for a requirement is not always trivial and requires a bit of experience with the boilerplates method. [20]

However, this is not unique to DODT; the same thing would apply to any other tool, whether it is for requirements, modelling or a new programming language.

9.3.4 Hazard identification

Although no general conclusions can be drawn from such a small case study, the results seem promising, since the hazards identified by DODT were approximately the same as in the requirements document for the existing *fuel level display* system. As was stated previously, the hazards related to the concepts in the requirements were derived from the more general concepts in the ontology (e,g, the hazards identified for the *fuel level gauge* actually came from the *gauge* concept).

If the above results hold for larger systems as well, the tool may be able to both reduce manual work and to ensure that likely sources of hazards are not forgotten. However, there is no guarantee that all hazards will be detected, so an experienced engineer should always review the result manually, and if necessary add missing hazards.

In the case study, the failure modes were associated with the components themselves. In an ISO 26262 setting, this kind of hazard analysis would correspond to activities done at, or below, the Functional Safety Requirements level.

Part V:
Discussion

10. Discussion

In the introduction, the following question was posed: *is it possible to achieve unambiguous requirements in a context of functional safety and ISO 26262?*

The short answer, based on the findings in earlier chapters is that "*it depends*".

There is no evidence that unambiguous requirements are unachievable, although it certainly is no trivial task to get it done for a complex in-vehicle E/E (Electrical/Electronic) system. However, as has been stated and demonstrated in earlier chapters, requirements specified in natural language are inherently ambiguous. At the same time, ISO 26262 state a strong preference that requirements should be written in natural language.

If the interpretation is made that the preference towards natural language indeed is a demand, then the answer must be *no*. On the other hand, ISO 26262 is rather ambiguous in both its own definitions and its requirements. This gives some leeway for interpretations.

For example, if, as was suggested in Chapter 7, the rationale is that all stakeholders should be able to read the requirements without requiring training in formal methods, then it should also be acceptable to

a) use a CNL (Constrained, or Controlled, Natural Language) together with an ontology in order to ensure that only well-defined concepts that relate to each other are used, or

b) use a formal notation and then translate the formally specified requirements into a corresponding natural language representation. To preserve the unambiguousness, the formal version should have precedence over any derivations.

If any of the above alternatives could be done, then the answer would change to *yes*. To achieve even more quality, the ontology approach could be used when transforming formal requirements into natural language derivations.

It must of course be stated that there are no methods or techniques that in themselves will guarantee unambiguous requirements; the results will depend on how the methods or techniques are executed.

In the sections below, a number of more specific topics are discussed. Most of them connect directly to points made in the previous chapters, but a few also discuss findings that have been made during the process but were too small to merit a dedicated chapter.

10.1 Ambiguities in ISO 26262

A lot of effort has been put into understanding the requirements in ISO 26262. One reason for this is that important concepts are poorly or ambiguously defined. This is slightly ironic since the ISO 26262 forbids such things for organisations that wish to comply with the standard. It should be noted that this thesis only focused on a very small part of the standard. Other parts may be more completely defined. In any case, some of the more problematic areas are summarised below.

- There are no definitions of syntax, semantics or natural language.
- The definitions of informal notation, semi-formal notation and formal notation are vague and ambiguous.
- The definition of SGs (Safety Goal) is ambiguous: is a SG considered a requirement or not?
- There is an implicit assumption that requirements only will exist in one notation.
- There are contradictory directives regarding interpretation of tables.
- It is unclear whether a formal notation can replace a semi-formal one. According to the definitions, it should be acceptable, but according to the tables, the opposite may apply.

ISO 26262 also seems to have an ambivalent and inconsistent approach towards formal methods. Although natural language is preferred, and semi-formal methods always is highly recommended where formal methods are merely recommended, the standard do mention formal methods and formal notations in several places. However, as the standard is being interpreted at Scania, the semi-formal methods must be deployed in any case. Few organisations are likely to bother doing both, and so will be satisfied with the semi-formal method. Nevertheless, why bother writing about formal methods if it always must be done after everything else has been done?

For good or bad, the standard also seem to have some prejudices about programming languages. For example, ISO 26262-6 Clause 8 recommends against, or for higher ASILs (Automotive Safety Integrity Level), strongly recommends against the use of recursion. While this certainly makes sense for imperative languages such as C, the consequence is that it also recommends against functional programming languages. Nevertheless, it can be argued that functional languages are at least as suitable, if not more so, for the development of safety-critical systems. For example, the functional language ML was developed for the purpose of mathematically proving properties in programs. Another example is Erlang, which was created for the purpose of developing software in telephone switches. In telephone switches, reliability is of paramount concern, and this has influenced the language. It should be noted that reliability is not the same as safety, but they are related to each other. It is hard to build a safe system without considering reliability. Additionally, Erlang has recently been applied outside the telecom industry, for example in situations where availability or low transaction times are important.

Although this thesis may appear to be critical against ISO 26262, it must be pointed out that an organisation that would follow the standard in order to produce safer systems are likely to do so. However, as with every standard, it is probably possible to get certified, and still not follow the intentions of the standard. The differences will all lie in whether the standard is used as a tool to achieve functional safety, or merely adhered to on paper to comply with future regulations.

10.2 Uniform management of requirements

ISO 26262 only applies to requirements related to functional safety. However, the majority, if not all, systems will have other requirements on them regarding e.g., performance or availability. Such requirements may be managed in a different manner, since there are no demands for change control, unambiguousness, or any other of the aspects covered in Chapter 6. Of course, other standards may apply which also mandates good requirements management. In any case, experience shows that ignoring the requirements part in projects is a good way towards delays and increased costs.

In Chapter 6, it was stated that it would be difficult to fulfil the demands stated by ISO 26262 by the means of documents alone. An organisation could instead choose to use a RDM (Requirements Definition and Management) system dedicated for the functional safety aspects in order to comply with ISO 26262.

On the other hand, if *all* requirements (i.e., not only safety-related requirements) were to be placed in a RDM system with support for change management, traceability, and workflows, it could become possible not only to comply with ISO 26262, but also gain economic benefits from an automated impact analysis. If it can be shown that a particular part of a system is not affected during a modification, then there is no need to spend time and other resources on testing it. There are also other reasons for using a single system for all requirements independent of type. Some of these are listed below in no particular priority:

- It is usually more cost effective to use and maintain a single system.
- If a single system is used, more effort and resources can be put into its continuous improvement. It has potential to become a system that supports the engineers in their daily work, as opposed to a system that must be used purely to comply with the standard. In the latter case, the system would probably be seen as burden, and compliance to ISO 26262 would be lip-service rather than a way to build safe systems.
- A good RDM system can provide benefits to the development process regardless of ISO 26262. However, much of those advantages are dependent on that all requirements exist in the same system.
- While it is theoretically possible to separate functional safety requirements from those that are not safety-related, the distinction may be harder in reality. The engineers would have to consider, for each requirement, in what system it should be managed. This would likely be frustrating and also prone to mistakes. Additionally, during a system modification, a requirement might be revised so that it suddenly becomes safety related. In that case, that requirement (and all refinements and dependencies) would have to be moved to the requirement management system responsible for functional safety. However, in addition to the extra administration, it would most likely also break the traceability in the original system.

10.3 Domain ontologies, boilerplates and DODT

Chapter 9 described a case study where DODT (Domain Ontology Design Tool) was used to demonstrate the potential benefits of using a domain ontology. Automatic refinement of natural language requirements into boilerplates was also demonstrated. It was found that both techniques had potential for reducing ambiguity in requirements. In this section, some considerations that was not covered earlier will be discussed.

One challenge that relates to the case study itself is the a priori knowledge about the fuel level display. As was briefly remarked, the domain knowledge regarding the *extractable* fuel level was included in the system definition and also in the ontology and the requirements. On the other hand, the scenario stated that the system would be developed without more prior information than what was available in the *Driver's Manual*. Still, when the person who writes the requirements is aware of relevant domain knowledge, it can be argued that it makes sense to use it, if not for no other reason that it might save an extra iteration later on, because such information is likely to appear sooner or later in any case.

In the last part of Chapter 9, it was noted that the quality of the ontology is important for the success of the technique. It was also found that concepts in the ontology preferably should be quite stable (i.e., not be modified unless strictly necessary). Therefore, much consideration must be given to how an ontology should be managed. Some important questions are:

1. Should there be one central, corporate-wide ontology, or multiple smaller ontologies, e.g., for different departments or even systems?
2. Who should be allowed to suggest new entries for inclusion in the ontology?
3. Who should perform the reviewing of new concepts?
4. Should it be allowed to change an existing item? If so, in what circumstances?
5. What should be the primary language in the ontology?
6. Who should be responsible for the ontology?

No clear answers exists to the above questions, because they are primarily of an organisational rather than a technical nature.

However, Scania do have valuable experience with these kind of systems from the Scania Lexicon and Scania Checker. In the case of the Scania Checker, the database was centrally managed, but the interface offered an easy way of submitting new terms for review and inclusion. The Senior Language Advisor at Scania [39], who is in charge of the Scania Checker and the subsequent tool Acrolinx IQ, is convinced that a central ontology is the best approach. The main argument is that the purpose of an ontology or a lexicon is to achieve a common repository of concepts; if multiple ontologies were to be used, e.g., one for each department, there is a high risk that identical terms with disparate meanings will be defined.

Even though there are strong arguments for a central system, it may be useful to distribute the administration so that decisions can be taken close to the engineers who would use the system. In order to succeed, it is important that domain experts and terminologists cooperate closely in order to get a qualitative ontology. How this should be done fast enough to avoid stalling the development is outside this discussion, but Scania appears to have managed a good workflow in the Scania Checker project, so it should be possible in this case as well.

Although the discussion about ontologies has so far mostly dealt with the challenges associated with the technique, the intention is not to discourage its use. The technical part is no more complicated than other information systems, but as usual, the main challenge is how the technique is to be used.

If the organisational aspects can be solved, and an ontology-based tool like DODT could be used for all systems, it would mean that all requirements would exist in the same database. While this in itself can be achieved by any decent RDM system, the ontology gives at least two additional advantages:

I. Possibility to extract information about which systems have requirements on a particular part or subsystem in the vehicle even though it is not explicitly listed.

II. Possibility to automatically find conflicts or inconsistencies globally, i.e., between different systems. An example is if the systems A and B requires mutually exclusive output from the component X. In addition to inconsistencies, the other metrics described in Chapter 8 are of course also valuable in order to increase the quality of the requirements.

Even more interesting, if the capabilities of DODT could be integrated in a full-fledged RDM system, in turn supporting or integrating the tools used by the technical writers, the following benefits can be gained (as opposed to using a traditional RDM system):

I. less ambiguous requirements,

II. improved understanding between different departments, and

III. increased possibility for future automated translation.

Finally, it could also give engineers and managers real-time information about the current status for each system.

10.4 Notations - which one is best?

In this thesis, different types of notations have been covered. Another major consideration has been the applicability of formal methods. Although no evaluation has been done where the different techniques have been independently compared to each other in the context of a real system, some thought have been given to the fitness of each notation and technique. The question that may very well be asked, then, is "which notation is the best one in general and for Scania?"

Unfortunately, there is no clear answer to that. If it was, it can be surmised that most businesses already would be using that technique.

One thing that usually is held against formal notations is that they require training before they can be used. This is of course not denied by the proponents of such notations or methods, and it is also one of the reasons that this thesis was unable to perform the originally planned evaluation of three different formal notations – it was simply to complicated without prior experience.

Additionally, there are several formal methods available, and where one method might be a close fit for a particular project, it may be unsuitable for the next one. All methods have their strengths and weaknesses. As if that was not enough, it may be not a good idea to use formal methods throughout an entire project, but rather in smaller parts where e.g., safety is of paramount concern.

On the other hand, there appears to be some prejudice against mathematical methods and symbols in the context of programming, which probably affects the uptake of formal methods. This is a bit strange since programming and computer science to a large extent are applied mathematics. To quote Hall: "People have a fear of new symbols, but mathematical symbols are introduced to make mathematics easier, not more difficult" [25]. Abrial, of the *B* language fame, goes one step further:

> We also hear very frequently that we must hide the use of mathematical notation because engineers will not understand it and be afraid of it. This is nonsense. Can we imagine that it is necessary to hide the mathematical notation used in the design of an electrical network because electrical engineers will be frightened by it? [1]

Be that as it may; what seems to be clear is that formal methods do have a lot of benefits, but that they also require both commitment and training to succeed. What, then, about the other end of the scale, namely informal notations?

In the previous statement that training is necessary before formal notations can be used for writing requirements, it seems to exist an unstated assumption that this is not required for natural language. However, as was shown in previous chapters, natural language is highly ambiguous. It can be discussed whether it is even theoretically possible to write a set of unambiguous requirements in natural language.

On the other hand, surely it must be possible to write *good enough* requirements in natural language? This is not an unrealistic assumption, but it can definitely be discussed, since there is a lack of literature showing successful examples. Furthermore, even assuming that it indeed can be done, another question arise: will it take less time to attain the experience and skills of writing *good enough* natural language requirements as opposed to attend a course in formal methods? For example, Leeb-Lundberg [38] found that it takes more than three semesters for students of law to learn how to use a specific juridical term correctly. In this case, "correctly" means it is used in the same way that experienced law professionals do. The comparison is relevant because juridical language attach domain-specific meaning to certain words in the same way that is done in the field of engineering. The results suggest that it may take considerable effort to become proficient in writing natural language requirements correctly.

Unfortunately, it appears that requirements written natural language without any supporting tools are doomed to remain highly ambiguous. In the future, with the support of more capable proof techinques, formal methods are likely to be increasingly deployed. Organisations that embrace such methods and notations are likely to gain a competitive edge because their products will have less defects, and also because formal methods do not work well with the ad hoc programming that is commonly in use today. More structured approaches to software development means less redesign and less bug fixing, which further decrease development costs and, even more importantly, decreases the ever more important time to market.

In the meantime, it appears to be worthwhile to consider semi-formal approaches, and especially techniques that use CNLs. Such techniques will probably prove to be useful regardless of the adoption of formal methods, because they can reduce the ambiguity when communicating with customers and other stakeholders.

Part VI:

Conclusions and future work

11. Conclusions

This chapter contains the key points of the previous chapters. Before going into the conclusions in depth, an introduction by way of looking into the past is provided.

More than 35 years ago, Frederick P. Brooks wrote his renowned book *The mythical man month*. Eleven years later he wrote the paper *No silver bullet* where he postulated that most of the easy problems in computer science had been solved, and what remained was the intrinsic problem that writing good software is hard. Both the *No silver bullet* paper and the original book as well as some additional chapters are available in the 20th anniversary edition of *The mythical man month* [11]. There, it can be read (emphasis original):

> *I believe the hard part of building software to be the specification, design, and testing of this conceptual construct, not the labour of representing it and testing the fidelity of the representation.* [. . .] If this is true, building software will always be hard. There is inherently no silver bullet.

What Brooks stated in 1986 seems to be true in 2011 as well. Tools, languages and techniques will never be enough: the major challenges lies in the process. However, the process can be made much more efficient with the correct tools.

11.1 Requirements in general

The conclusions in this section cover different aspects of requirements definition and management. Requirements is an important part of ISO 26262, and it will be virtually impossible to fulfil the directives in ISO 26262 without a lot of considerations on how requirements will be specified and managed throughout the system life-cycle.

I. Writing good requirements are much harder than it appears, regardless of form or notation.

II. Formal methods can reduce ambiguity and increase confidence about the safety of a system.

III. Formal methods do take some effort to understand, and even more effort to become proficient in. However, it is not certain whether it takes longer to learn formal methods than to become so experienced in writing natural language requirements that most ambiguities can be avoided.

IV. Top-level requirements should not be treated in isolation; it is important to create traceability throughout the development process.

V. A good RDM (Requirements Definition and Management) system is necessary to achieve recommended and, by ISO 26262 mandated specification and management of requirements.

VI. According to literature and research (see Chapter 6), a lot of money is wasted due to lack of good requirements. Bad requirements are also likely to lead to *waste*, which goes against the first Lean principle ("Eliminate waste") as described by Mary and Tom Poppendieck [44].

11.2 Requirements, ambiguity and ISO 26262

The following four conclusions together answer the main question formulation of the thesis (*is it possible to achieve unambiguous requirements in a context of functional safety and ISO 26262?*):

I. Writing unambiguous requirements in natural language is unfeasible, if not outright impossible.

II. ISO 26262 has a strong bias towards natural language for requirements specifications, while at the same time demanding unambiguous requirements.

III. Assuming that I and II are true, then it is not possible to comply with ISO 26262.

IV. However, if the bias in ISO 26262 towards natural language is interpreted to mean that there shall exist a *version* of a requirement that can be *interpreted* as a natural language statement, then it becomes possible to comply with the ISO 26262.

Furthermore, two additional conclusions regarding ISO 26262 are worth pointing out:

I. ISO 26262 is not written in adherence to its own directives. The standard demands that requirements must be unambiguous and comprehensible, but in the standard itself, many requirements are using concepts that are ambiguous or not defined at all.

II. ISO 26262 is written in a way that makes formal methods the "second choice" after semi-formal methods (which is an undefined concept itself). This is likely to make organisations avoid using formal methods even though both research and practical experience demonstrates a particular suitability for such methods in safety-critical systems.

11.3 Ontologies and constrained natural language

Domain ontologies can be thought of as a (domain specific) database of concepts and relations between them. The following conclusions are derived primarily from the case study in Chapter 9 and from conservations with the Senior Language Advisor at Scania. In the case study, a research tool named DODT (Domain Ontology Design Tool) was used to write requirements with the support of an ontology. Furthermore, a CNL (Constrained, or Controlled, Natural Language) in the form of boilerplates was used to refine the natural language requirements.

I. A key factor for reducing ambiguousness is to use a shared vocabulary between all stakeholders. A domain ontology is one way to achieve this. The ambiguity can be further reduced by imposing restrictions on the syntax, e.g., by using a CNL.

II. One advantage of domain ontologies is that metrics on the requirements quality can be established (see Chapter 8). This makes it easier to detect problems in the requirements.

III. By integrating domain ontologies and CNLs in the requirements specification process, e.g., by a tool such as DODT, the quality of the requirements can be further increased. In order to manage the traceability requirements in ISO 26262, it may be necessary to integrate the capabilities of DODT in a larger system.

IV. Change management of the ontology itself will be necessary if the requirements will be depending on the concept definitions in the ontology. It may also be necessary to manage the dependencies between the requirements and the ontology concepts, but this depends on the implementation.

V. The major challenge in applying an ontology is to make it easy enough to update but without losing quality. For shared ontologies, central administration is necessary, but this is mainly an organisational question rather than a technical one. However, Scania has previous experience with managing such processes, so it seems plausible that a good balance can be achieved.

12. Future work

Below are a some suggestions for how the results of this thesis can be extended, as well as other identified issues that might merit further research. These are divided into two categories: those that are applicable mainly for Scania and those of a more general nature.

12.1 Scania specific

Evaluate different formal notations and methods

Both research and practical experience shows that formal methods can provide multiple benefits during specification and development. It would be interesting to apply different methods to the same system that was used in this thesis (the fuel level display) and evaluate the fitness from a Scania perspective.

Evaluate RDM (Requirements Definition and Management) *systems*

A key finding is that documents are unsufficient for requirements storage and management if traceability and change management is desired. However, such systems will have a profound effect on the organisation. Therefore, a throughout investigation of the actual needs should be done before any solution is purchased or developed. Indeed, it may be the case that in order to cope with ISO 26262, a larger system which can support the entire system life-cycle may be necessary.

Evaluate DODT on a larger scale

While the case study in Chapter 9 showed great promise, it would be interesting to try it in a larger scale. As a first step, all requirements for the fuel level display system should be added, but preferably also requirements from other systems. This could give additional insights in both the number of required boilerplates as well as potential problems with the ontology technique. Additionally, integration with RDM systems could be investigated.

Investigate potential synergy effects by using an ontology more extensively

Since both the After Market and the Research and Development departments have similar challenges in regard to the lack of consistent vocabulary, and also because it would be efficient if both departments used the same vocabulary, it could be investigated how this can be achieved.

Investigate the possibility to automatically generate natural language versions from a formal notation

It was postulated that since formal notations have both complete syntax and semantics, it should be feasible to automatically generate a natural language version from the formal one. This postulate merits further research, and could be especially fruitful since Scania has considerable experience in the field of language management.

12.2 General

Cooperate with ISO in order to improve ISO 26262

If some of the ambiguity and vagueness in ISO 26262 could be removed, the interpretation of the standard would be more predictable. Additionally, it may be that some parts of the standard are interpreted in a way that the authors of the standard did not intend, which of course would be unfortunate.

Evaluate SBVR and OCL

In Chapter 4 ("Related work"), SBVR (Semantics of Business Vocabulary and Business Rules) and OCL (Object Constraint Language) were described as something similar to domain ontologies and boilerplates. Although the latter concept was chosen due to the tool DODT (Domain Ontology Design Tool) and also due to the connection with the CESAR Project, both SBVR and OCL merits a further investigation, especially since it seems to be possible to automatically generate source code from OCL.

Combine SBVR with domain ontologies

In the tool DODT, domain ontologies are combined with boilerplates. It would be very interesting to see what could be done if a domain ontology instead was combined with SBVR and potentially also OCL.

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