The Six-Variable Model
Context Modelling Enabling Systematic Reuse of Control Software

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Keywords: Four-Variable Model, Context, Context Modelling, Contextual Decision, Satisfaction Argument, Domain Knowledge, Requirement, Specification.

Abstract: A control system usually consists of some control software as well as sensors and actuators to monitor and control certain quantities in the environment. The context of the control software thus consists of the sensors and actuators it uses and the environment. When starting development of the control software, its context is often not predefined or given. There are contextual decisions the developers can make (e.g. which sensors/actuators/other systems to use). By means of these decisions, the context is defined step by step. Existing approaches (like the Four-Variable Model) call for documenting the environmental quantities (monitored, controlled, input, and output variables) that are relevant after making these contextual decisions. The environmental quantities that have originally been relevant (i.e. before deciding which sensors/actuators/other systems to use) are not documented. This results in problems when the software shall later on be reused in another, slightly different setting (e.g. with additional sensors). Then, it is hard for developers to decide which environmental quantities are still relevant for the software. In this paper, we suggest an extended version of the Four-Variable Model, the Six-Variable Model, and, based on that, a context modelling method, that combines existing approaches. The benefit of our method is that the environmental quantities that are relevant before and after decision making are documented as well as the contextual decisions themselves and the options that were selectable. In this way, later reuse of the software is facilitated.

1 INTRODUCTION

A control system usually consists of the control software as well as sensors and actuators for monitoring and controlling the environment (Parnas and Madey, 1995). The context of the control software comprises the sensors and actuators it uses as well as the environment it monitors/controls by means of them (Jackson, 2001). So, context modelling refers to modelling or documenting this context.

The famous Four-Variable Model was suggested by Parnas and Madey in 1995 and focuses also on control systems (Parnas and Madey, 1995). It defines the content of software documentation. Software documentation consists of different types of documents (e.g. System Design Document, Software Requirements Document). Parnas and Madey describe these documents as representations of one or more mathematical relations. These relations exist between the following four types of variables: monitored variables *m* (environmental quantities that the software monitors through input devices, e.g. sensors), controlled variables *c* (environmental quantities that the software controls through output devices, e.g. actuators), input variables *i* (data items that the software needs as input), and output variables *o* (quantities that the software produces as output). These four variables are illustrated in Figure 1 together with a train control software as an example.

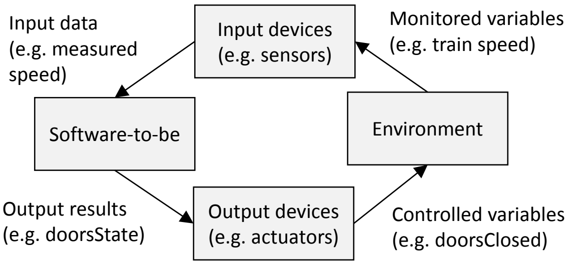


Figure 1: Four-variable model as illustrated in (van Lamsweerde, 2009).

In case of the train control software, the physical speed of the train is the monitored variable and the measured speed is the input variable. The differentiation is important because these two variables might be different. Consider, for example, aquaplaning. In this

Ulfat-Bunyadi, N., Meis, R. and Heisel, M.
The Six-Variable Model - Context Modelling Enabling Systematic Reuse of Control Software.
DOI: 10.5220/0005944100150026
In *Proceedings of the 11th International Joint Conference on Software Technologies (ICSOFT 2016) - Volume 2: ICSOFT-PT*, pages 15-26
ISBN: 978-989-758-194-6

case, the measured speed of the train might be lower than the actual speed of the train. The measured speed might even be 0 km/h although the train is actually still moving. The same holds for output variables and controlled variables. The output variable ‘doorsState’ might be set to ‘closed’ but it could still happen that not all train doors are actually closed. However, as we will show in the following, documenting only four variables is insufficient. There are actually six variables that need to be documented.

As an example, we consider Adaptive Cruise Control (ACC) software (Robert Bosch GmbH, 2003). The main objective of the software is to maintain the driver’s desired speed while keeping the safety distance to vehicles ahead. To identify vehicles ahead that are driving on the same lane, the ACC software needs to ‘know’ the speed, the distance, and the lane of vehicles ahead. To gain this information, the ACC software uses a long range radar sensor and ESP (Electronic Stability Program) sensors. The long range radar (LRR) detects vehicles ahead and provides information about their speed, distance, and lateral offset. The ESP sensors measure wheel speed, yaw rate, lateral acceleration, and steering wheel angle of the ACC vehicle itself. The ACC software uses all this data in the following way: Based on the data from the ESP sensors, the ACC software calculates the yaw rate corrected for offset. This value enables the ACC software to predict the course of the ACC vehicle. Based on the lateral offset of vehicles ahead (provided by the LRR) and the predicted course of the ACC vehicle, the ACC software calculates the course offset of vehicles ahead. The course offset is the estimated relative position of the vehicle ahead. In this way, the ACC software estimates whether a vehicle ahead is driving on the same lane or not. According to the Four-Variable Model (Parnas and Madey, 1995), the input and monitored variables given in Table 1 would be documented.

Table 1: Input and monitored variables for ACC example.

Sensor	Input variable	Monitored variable
LRR	speed, distance, lateral offset of vehicles ahead	speed, distance, relative position of vehicles ahead
ESP	wheel speed, yaw rate, lateral acceleration, steering wheel angle of ACC vehicle	course of ACC vehicle

In contrast to that, the variables that were actually relevant (i.e. before making the decision to use the long range radar and the ESP sensors) are: the speed, the distance, and the lane of vehicles ahead as well as the lane of the ACC vehicle. Yet, these are not documented. This situation results in problems when the ACC software shall later on be reused in another setting. Imagine that the ACC software shall later on be reused in the next car generation. However, in the next generation, the ACC vehicle is additionally equipped with a stereo video sensor which provides precise information about the lane of vehicles ahead and the lane of the ACC vehicle. Having documented only the information given in Table 1, it is quite hard for developers to decide which input and monitored variables are still necessary and which ones are not.

In summary, the context of the software-to-be is not completely predefined or given. Developers make contextual decisions and thereby define the context step by step. Existing approaches (like the Four-Variable Model (Parnas and Madey, 1995) but also others; see Section 5) only call for documenting the variables that are relevant after decision-making, i.e. the classical four variables. None of the approaches calls for documenting the contextual decisions that are made (together with the options that were selectable) and the variables that have been relevant before decision-making. In this paper, we suggest a context modelling method that ensures the documentation of all this information. Our method is based on an extended version of the Four-Variable Model which we call the Six-Variable Model.

The paper is structured as follows. In Section 2, we present some fundamental concepts that provide the basis for our work. In Section 3, we introduce our Six-Variable Model. Section 4 contains a description of our context modelling method which is based on the Six-Variable Model and combines existing approaches. We discuss related work in Section 5 and finally conclude our paper in Section 6.

2 FUNDAMENTALS

We use the terminology defined by Zave and Jackson (Zave and Jackson, 1997) and differentiate between system, machine, and environment. A *system* consists of manual and automatic components. The *machine* is the computer-based artefact of the system that is the target of software development. The *environment* is a portion of the real world that is becoming the environment of the development project because its current behaviour is unsatisfactory in some way. The machine will be inserted into the environment so that the behaviour of the environment becomes satisfactory.

There are indicative and optative statements about the environment. *Indicative statements* describe the environment as it is without or in spite of the machine. *Optative statements* describe the environment as we would like it to be because of the machine. Based on this differentiation, requirements, domain knowledge, and specification are defined as follows. A *requirement* is an optative statement, intended to express the desires of the customer concerning the software development project. *Domain knowledge* or *domain assumptions* represent indicative statements intended to be relevant to the software development project. The *specification* is an optative statement, intended to be directly implementable and to support satisfaction of the requirements. The relation between the set of requirements (R), the set of domain knowledge/assumptions (K), and the set of specifications (S) is defined by means of the *satisfaction argument* given in Equation 1.

$$S, K \vdash R \qquad (1)$$

The satisfaction argument says that if a machine is developed that satisfies S and is inserted into the environment as described by K, then the set of requirements R is satisfied.

3 OUR SIX-VARIABLE MODEL

We first describe how we derived the Six-Variable Model based on the Four-Variable Model (see Section 3.1). Then, we explain the notation that might be used to document the six variables (see Section 3.2). Finally, we introduce four so called domain knowledge frames that can be used to make assumptions that are implicit in the Six-Variable Model explicit (see Section 3.3).

3.1 Derivation of the Model

As explained above, Parnas and Madey (Parnas and Madey, 1995) define not only the four variables (monitored, controlled, input, and output) but also the following mathematical relations between them:

- NAT: indicative relation between m and c
- REQ: optative relation between m and c
- IN: indicative relation between m and i
- OUT: indicative relation between o and c
- SOF: optative relation between i and o

On the one hand, the environment (i.e. nature and previously installed systems) places constraints on the values of the environmental quantities m and c. These are described by NAT. On the other hand, the software-to-be is expected to impose further constraints on them. These are described by REQ. IN describes how sensors translate m to i. OUT describes how actuators translate o to c. SOF, finally, describes how the software-to-be will/shall produce its output o from the input i.

As explained in the introduction, we argue that documenting only the classical four variables is insufficient. The four variables result from the decision which sensors/actuators/other systems to use for monitoring/controlling quantities in the environment. The quantities that were originally relevant in the requirement are often different than the ones that are finally monitored/controlled. In the ACC example, the lane, speed, and distance of vehicles ahead as well as the lane of the ACC vehicle were environmental quantities that were originally relevant. Yet, due to the decision to use a long range radar and ESP sensors for monitoring, other environmental quantities were monitored: the relative position, speed, and distance of vehicles ahead as well as the course of the ACC vehicle. Therefore, we extend the Four-Variable Model with the following two variables:

- *referenced variable r*: environmental quantities that should originally be observed/monitored and were therefore referenced in the requirement
- *desired variable d*: environmental quantities that should originally be influenced and that shall be as desired by the requirement

The introduction of the two new variables necessitates that the following mathematical relations between the variables are described as well:

- IN_{RW}: indicative relation between r and m
- OUT_{RW}: indicative relation between c and d
- NAT_{RW}: indicative relation between r and d
- REQ_{RW}: optative relation between r and d

IN_{RW} describes how a referenced variable is related to a monitored one (e.g. how lane of vehicles ahead is related to relative position of vehicles ahead). Note that there does not necessarily need to be a 1-to-1 mapping between the variables. Actually, lane of vehicles ahead is not only related to relative position of vehicles ahead but also to course of the ACC vehicle, since both are used to estimate the lane of vehicles ahead. So, there may be a 1-to-n, n-to-1, n-to-m mapping between r and m variables. Similarly, OUT_{RW} describes how controlled variables are related to desired variables. Beyond that, there is an indicative and an optative relation between the newly introduced r and d variables. These are documented by means of the relations NAT_{RW} and REQ_{RW}. We will explain these relations later on in more detail.

3.2 Documentation of the Six Variables

For documenting the six variables, Jackson's problem diagrams (Jackson, 2001) are well suited. Jackson differentiates between the world (i.e. the environment) and the machine (i.e. the software-to-be). The software development problem to be solved is in the real world, the environment. The machine is inserted into this environment to solve the problem. In problem diagrams, the machine and its connection to the problem/requirement in the real world can be modelled in terms of so called problem domains that are in between. The six variables can also be made explicit: they can be documented as phenomena at the different types of connections between the domains. We first introduce the notation and then explain the documentation of the six variables in more detail.

According to Jackson's method (Jackson, 2001), first, a context diagram is created showing the machine in its environment. Then, the overall software development problem is decomposed into subproblems, and each subproblem is documented in a problem diagram. As a support in creating problem diagrams, Jackson provides so called problem frames, which are patterns of recurring software development problems. They are intended to be used when decomposing software development problems by instantiating them.

A context diagram consists of the following modelling elements: the machine domain (representing the software-to-be), usually several problem domains (representing any material or immaterial object in the environment, e.g. people, other systems, a physical representation of data), and interfaces (of shared phenomena, e.g. events, states, values) connecting the machine domain and problem domains. At the interface, not only the phenomena are annotated but also the abbreviation of the domain controlling the phenomena followed by an exclamation mark (e.g. M!). The other domain that participates in the interface observes these phenomena. An example of a context diagram is given in Figure 11.

Additionally to the elements of a context diagram, a problem diagram contains a requirement, a constraining reference, and optionally one or more requirement references. A requirement reference connects the requirement and a problem domain expressing that the requirement refers somehow to the domain phenomena. A constraining reference connects also the requirement and a problem domain, but expresses that the requirement not only refers to but even constrains the domain phenomena. An example of a problem diagram is given in Figure 12.

In Figure 2, we have depicted the Six-Variable Model itself as a problem diagram. The software-to-be is the control machine. Sensors and actuators are used by the machine to monitor/control the environmental domains W and Z. Jackson calls the sensors and actuators connection domains. A connection domain is a domain that is interposed between the machine and a problem domain (Jackson, 2001). There are reliable and unreliable connection domains. According to Jackson, they shall only be modelled if they are unreliable. If they are reliable, they can be omitted in the problem diagram. As regards our Six-Variable Model, note that there are maybe several connection domains (i.e. a chain of sensors or a chain of actuators) between the machine and the environment, especially in embedded systems. For an example, consider again the ACC system described above. The driver may press the brake pedal to deactivate ACC. Yet the brake pedal is not directly connected to the ACC. The brake pedal is connected to two sensors: a travel sensor and a pressure sensor to measure the speed and force of the driver's command. These sensors are connected to the ESP and the ESP is connected to the ACC. The existence of connection domains means that there are not only six variables to be documented but even $4+n$ variables. However, the method we present in this paper is already designed to consider the case that there may be more connection domains (see Section 4).

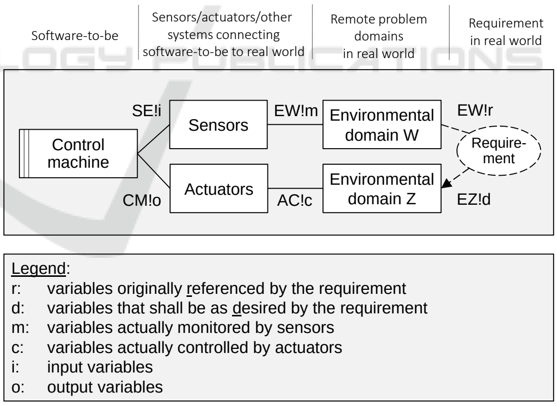

Software-to-be
Sensors/actuators/other systems connecting software-to-be to real world
Remote problem domains in real world
Requirement in real world
Control machine
SE!i
Sensors
EW!m
Environmental domain W
EW!r
Require-ment
CM!o
Actuators
AC!c
Environmental domain Z
EZ!d
Legend:
r: variables originally referenced by the requirement
d: variables that shall be as desired by the requirement
m: variables actually monitored by sensors
c: variables actually controlled by actuators
i: input variables
o: output variables

Figure 2: Our Six-Variable Model.

The mathematical relations between the six variables are depicted in Figure 3. We have renamed the requirement to be satisfied in the real world as RW-Req. Furthermore, we added two requirements: Sof-Req (the set of software requirements) and Sys-Req (the set of system requirements). Sof-Req is actually the specification SOF expressing how i is transformed into o. The system consists of the software (the machine) and the sensors and actuators. Therefore, Sys-Req represents the set of system requirements and refers to m while constraining c. RW-Req refers to r and constrains d. SOF, REQ, and REQ_{RW} are optative. The corresponding indicative relations between m and c as well as r and d are described by NAT and NAT_{RW}. Further indicative relations are IN, IN_{RW}, OUT, and OUT_{RW}.

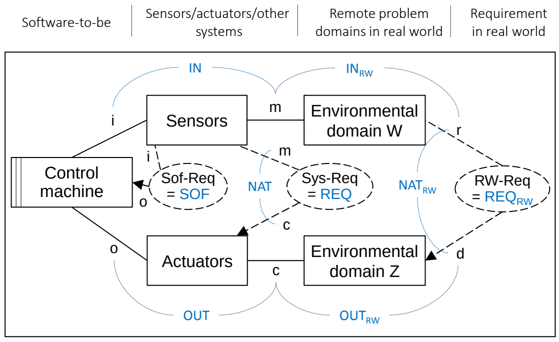


Figure 3: Relations among six variables.

3.3 Assumptions in the Six-Variable Model

According to Parnas and Madey, IN and OUT are indicative relations (Parnas and Madey, 1995). Yet, in our opinion, IN and OUT as well as IN_{RW} and OUT_{RW} can also be considered to be optative. We want these relations to be true, but they are not really facts. Rather, they are assumptions. Van Lamsweerde (van Lamsweerde, 2009) makes an interesting differentiation. He considers three types of domain knowledge: domain properties, domain hypotheses, and expectations. *Domain properties* are descriptive statements about the environment and are facts (e.g. physical laws). *Domain hypotheses* are also descriptive statements about the environment, but are assumptions. *Expectations* are also assumptions, but they are prescriptive statements to be satisfied by environmental agents like persons, sensors, actuators. We adopt van Lamsweerde's three types of domain knowledge and suggest four domain knowledge frames which can be used to make the expectations and domain hypotheses in the Six-Variable Model explicit. The domain knowledge frames are given in Figure 4. Each frame can be instantiated to create the corresponding domain knowledge diagram. Domain knowledge diagrams have already been introduced in (Alebrahim et al., 2014). However, the four domain knowledge frames we present here are new. The benefit of making domain hypotheses and expectations explicit is that (i) the developers of the machine become aware of them and (ii) the expectations can be discussed with the developers or providers of these sensors, actuators, and other systems and, thus, be reviewed by them.

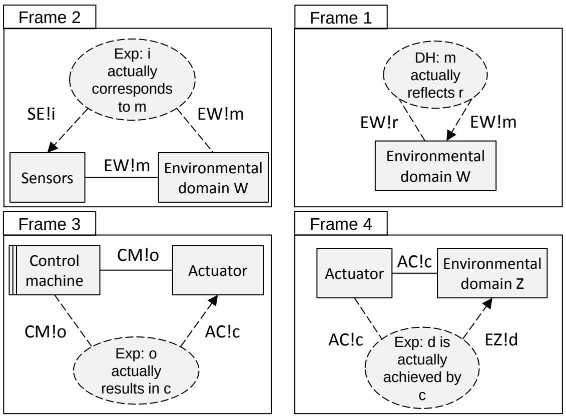


Figure 4: Domain knowledge frames.

Frame 1 in Figure 4 expresses that there is a domain hypothesis about the domain W which says that m actually reflects r. This is a domain hypothesis made by us (as the developers of the machine). Frame 2 expresses that there is an expectation to be satisfied by the sensor domain. The sensor domain has to ensure that i actually corresponds to m. Frame 3 expresses that there is an expectation to be satisfied by the actuator domain. The actuator domain has to ensure that o actually results in c. Finally, frame 4 expresses that there is an expectation to be satisfied by the controlled domain Z. Domain Z is responsible for ensuring that d is actually achieved by c. Note that we have a domain hypothesis in Frame 1 while Frames 2 to 4 present expectations. All four statements are assumptions. Yet, the difference lies in the prescriptive and descriptive character of the statements. In Frames 2 to 4, we make prescriptions for certain domains: for the sensor (Frame 2), the actuator (Frame 3), and the controlled domain (Frame 4). They are responsible for coming up to our expectations. Yet, in Frame 1, we cannot make domain W responsible for satisfying our assumption. It is rather a hypothesis we make which needs to hold.

4 CONTEXT MODELLING

In this section, we present a method that is based on the Six-Variable Model and supports developers in documenting not only the six variables but also the contextual decisions that are made as well as the options that were selectable. We explain the techniques we use and the reason why we chose them in Section 4.1. Afterwards, we present the method steps in Section 4.2. The application example is described in Section 4.3. Finally, we explain the benefit of the created models in Section 4.4.

4.1 Used Techniques

Problem Diagrams. As described in Section 3, problem diagrams (Jackson, 2001) are well suited for modelling the six variables, since they show the requirement, the remote problem domains, the connection domains, and the machine domain in one diagram together with the shared phenomena. Yet, developers need guidance in documenting the 'right' six variables therein and not other phenomena. We provide this guidance in our method (see Section 4.2). Although we use problem diagrams, we do not proceed in the way suggested by Jackson during problem decomposition. Our method proceeds in another way.

For creating the problem diagrams, we used the UML4PF tool (Cote et al., 2011). The benefit of using this tool is that different other analyses can be performed on the models that are created with this tool. In UML4PF, problem diagrams are shown as UML class diagrams with corresponding stereotypes to express the semantics of problem diagram model elements. For more details regarding the mapping of the notations, see (Cote et al., 2011).

Differentiating between Essence and Incarnation. The differentiation between essence and incarnation of a system was introduced 1984 by McMenamin and Palmer (McMenamin and Palmer, 1984). The essence comprises the capabilities that a system must possess to fulfil its purpose, regardless of how the system is implemented. The incarnation comprises all implementation details. A heuristic for identifying the essence of a system is the assumption of perfect technology, i.e. the assumption that the technology within the system is perfect, i.e. processors are, for example, able to do anything constantly and containers are able to hold an infinite amount of data. We use the differentiation between essence and incarnation in our method too. Yet, to identify the essence, we assume that the technology outside the machine is perfect. This means, for example, that connection domains like sensors and actuators are considered to be reliable and are therefore not shown in the corresponding context/problem diagram. To consider the incarnation, the assumption of perfect machine-external technology is then given up.

OVM and Selection Model. To document contextual decisions and options/alternatives, we use the OVM (Orthogonal Variability Model) (Pohl, 2010). The OVM was originally developed to capture the variation points and variants of a product line together with their variability dependencies (mandatory, optional, alternative choice) as well as constraint dependencies (requires, excludes). The variants can be related to a development artefact like a requirement or a diagram (or a part of it) by means of so called artefact dependencies. The artefact (or the part of it) is then defined as being variable. For documenting the choices that are made, a selection model is created. We use the OVM to document the contextual decisions to be made, the options/alternatives that are selectable, and dependencies among them. By means of artefact dependencies, we relate the alternatives to variable elements of the AND/OR graph (see next section). To document the choices, we also use a selection model. The strength of the OVM and the main reason for choosing this approach over others is that one is able to relate a variant to an entire model, a model element, or even certain sections of a model.

AND/OR Graph. For documenting the refinement/decomposition of requirements, we use an AND/OR graph (which is similar to the AND/OR goal graph described in (Pohl, 2010)). The AND/OR graph is a directed, acyclic graph with nodes that represent requirements and edges that represent AND-decomposition relationships and OR-decomposition relationships between the requirements. A decomposition of a requirement R into a set of subrequirements R_1,..., R_n is an AND-decomposition iff all subrequirements must be satisfied to satisfy the requirement R. A decomposition of a requirement R into a set of subrequirements R_1,..., R_n is an OR-decomposition iff satisfying one of the subrequirements is sufficient for satisfying the requirement R. What needs to be documented in addition to the AND/OR graph, is the reasoning why each AND/OR-decomposition is sufficient. We suggest documenting this information at least informally in natural language.

4.2 Method Steps

Figure 5 provides an overview of the method steps as well as the input and output of each step.

Step 1: Create an essential context diagram. As a first step, the remote problem domains are identified and a context diagram showing the machine domain, the remote problem domains, and the interface between them with the r and d variables is created (see Figure 6). The context diagram is essential, since we assume that the connection domains are all reliable and, thus, abstract from them. As input to Step 1, knowledge about the machine and its environment is needed.

Step 2: Create essential problem diagrams. During this step, the overall problem/requirement is decomposed/refined and, for each requirement, an essential problem diagram is created. The information to be documented in an essential problem diagram is given in Figure 7. An essential problem dia-

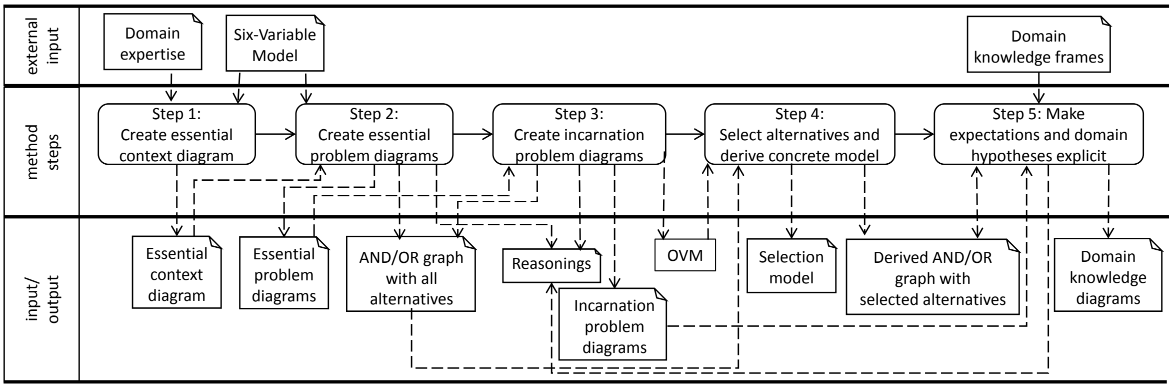

external input
method steps
input/ output
Domain expertise
Six-Variable Model
Domain knowledge frames
Step 1: Create essential context diagram
Step 2: Create essential problem diagrams
Step 3: Create incarnation problem diagrams
Step 4: Select alternatives and derive concrete model
Step 5: Make expectations and domain hypotheses explicit
Essential context diagram
Essential problem diagrams
AND/OR graph with all alternatives
Reasonings
Incarnation problem diagrams
OVM
Selection model
Derived AND/OR graph with selected alternatives
Domain knowledge diagrams

Figure 5: Overview of our context modelling method.

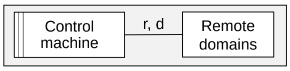


Figure 6: Information to be documented in an essential context diagram.

gram shows the machine (or more precisely the submachine), the remote problem domains, the requirement, interfaces between machine and remote problem domains annotated with *r* and *d* variables as well as requirement references and constraining references annotated with *r* and *d* variables. Through the refinement/decomposition of the requirement, the problem domains that were shown in the context diagram may also be decomposed into several ones. So it may be the case that the problem diagrams contain the decomposed problem domains. This is allowed as long it is ensured that all problem domains shown in the problem diagrams are either shown as well in the context diagram or represent parts of the problem domains shown therein. The decomposition of the overall problem/requirement may be done in several steps, if necessary. The decomposition relationships of the problems/requirements are documented as an AND/OR graph. For each AND/OR decomposition of a requirement, the reasoning why the decomposition is sufficient is documented too.

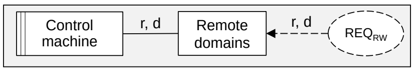


Figure 7: Information to be documented in an essential problem diagram.

Step 3: Create Incarnation Problem Diagrams. For each essential problem diagram from Step 2, connection domains (if existent) are added and thus incarnation problem diagrams are created. If there are different options/alternatives for using certain sensors/actuators (i.e. connection domains), create separate incarnation problem diagrams for each option/alternative. Figure 8 shows which information needs to be documented in an incarnation problem diagram. The main difference is that sensors and actuators are considered and, thus, the *m*, *c*, *i*, *o* variables are introduced. If there are options/alternatives, a decision point with the corresponding alternatives is also created in an OVM. Due to the new requirement decompositions, the AND/OR graph from Step 2 needs to be extended and corresponding reasonings need to be created. The decision points and alternatives in the OVM are related to the corresponding variable elements of the AND/OR graph by means of artefact dependencies.

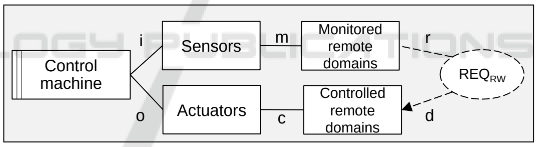
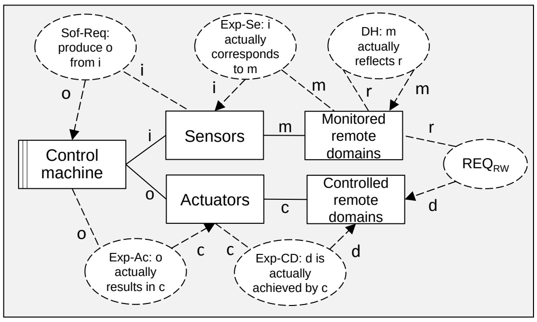


Figure 8: Information to be documented in an incarnation problem diagram.

Step 4: Select Alternatives and Derive Concrete Model. For each decision point in the OVM, one or (if possible and appropriate) several alternatives are selected. The choices are documented in a selection model. Based on the selection model, a concrete model of the requirement decomposition is derived from the AND/OR graph .

Step 5: Make Expectations and Domain Hypotheses Explicit. To each incarnation problem diagram that has been selected in Step 4, the four domain knowledge frames (introduced in Section 3) are applied to make the domain hypotheses and expectations explicit in separate domain knowledge diagrams. This results in a decomposition of the requirement from the incarnation problem diagram. We illustrate this in Figure 9. If the domain hypothesis DH is valid, the expectations Exp-Se, Exp-Ac, and Exp-CD are satisfied (by the sensors, actuators, and controlled domains), and the machine satisfies its software requirement Sof-Req, then the real world requirement REQ_{RW} is satisfied (see satisfaction argument in Figure 9). The derived AND/OR graph from Step 4 is extended with the requirement decompositions made in this step. Thus, the satisfaction argument is also reflected in the AND/OR graph. The reasoning for these decompositions need to be documented as well.


Sof-Req: produce o from i
Exp-Se: i actually corresponds to m
DH: m actually reflects r
Control machine
Sensors
Monitored remote domains
Actuators
Controlled remote domains
REQ_RW
Exp-Ac: o actually results in c
Exp-CD: d is actually achieved by c
i
o
m
r
c
d

Satisfaction argument: *DH, Exp-Se, Sof-Req, Exp-Ac, Exp-CD* $\vdash REQ_{RW}$

Figure 9: Progression towards the machine.

The application of the method results in a number of models that are related to each other. The inter-model relationships are depicted in Figure 10. Note that only those concepts of the models are shown that need to be related to each other. The relationships between the OVM/selection model and the AND/OR graph need to be documented as artefact dependencies. The relationships between requirements in the two AND/OR graphs (the one containing all alternatives/options as well as the one containing only the selected alternatives/options) and the requirements in the problem diagrams need to be documented as well by means of traceability relationships. The same holds for the relationships between the domain hypotheses and expectations (both representing domain knowledge) in the domain knowledge diagrams and the problem diagrams to which they contribute.

4.3 Application to Real Example

We applied our method to a real example: the ACC described in (Robert Bosch GmbH, 2003). Due to space limitations, we are not able to describe the entire example here and show only excerpts.

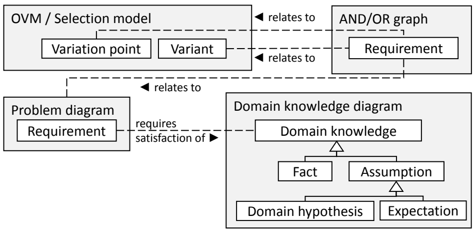


Figure 10: Inter-model relationships.

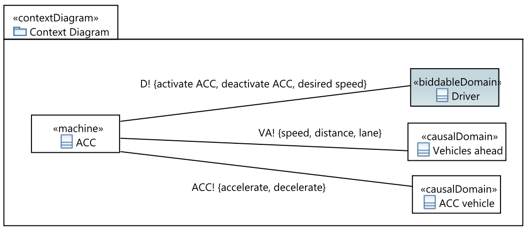

«contextDiagram»
Context Diagram
«machine» ACC
D! {activate ACC, deactivate ACC, desired speed}
«biddableDomain» Driver
VA! {speed, distance, lane}
«causalDomain» Vehicles ahead
ACC! {accelerate, decelerate}
«causalDomain» ACC vehicle

Figure 11: Essential context diagram for ACC example.

Step 1: Create an Essential Context Diagram. An essential context diagram for the ACC example is given in Figure 11. It shows three remote problem domains in the real world: the driver, vehicles ahead, and the ACC vehicle. Since we abstract from connection domains, the ACC machine is directly connected to these problem domains. The interfaces are annotated with the environmental quantities of these problem domains that we are interested (the *r* and *d* variables).

Step 2: Create Essential Problem Diagrams. The overall requirement R-0: "Maintain desired speed keeping safety distance to vehicles ahead." is decomposed into the following requirements:

R-1: Enable driver to activate ACC.
R-2: Enable driver to enter desired speed.
R-3: Identify vehicles ahead for tracking.
R-4: Adapt speed to desired speed keeping safety distance to vehicles ahead.
R-5: Display recorded desired speed to driver.
R-6: Enable driver to deactivate ACC.

The following reasoning explains why this decomposition is sufficient:

> *The decomposition into R-1 to R-6 is sufficient because: R-1 ensures that the ACC machine enters the "activated" state while R-6 ensures that the ACC machine leaves this state. In the "activated" state, the machine is able to satisfy R-2 to R-5 as follows. R-2 ensures that the driver may enter a new desired speed if he wants to. Otherwise, the ACC machine uses the currently stored desired speed. R-3 ensures that the ACC machine detects vehicles ahead driving on the same lane. R-4 ensures that the ACC machine not only drives at the desired speed but adapts the speed, if it detects vehicles ahead. R-5 ensures that the driver is always informed about the desired speed that is currently stored and used by the ACC machine.*

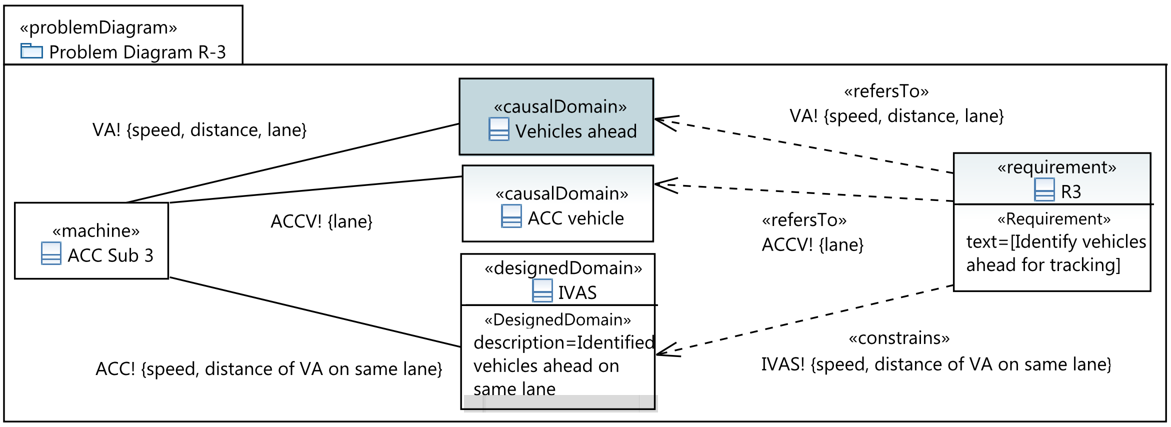

«problemDiagram»
Problem Diagram R-3
VA! {speed, distance, lane}
«causalDomain»
Vehicles ahead
«refersTo»
VA! {speed, distance, lane}
«machine»
ACC Sub 3
ACCV! {lane}
«causalDomain»
ACC vehicle
«requirement»
R3
«Requirement»
text=[Identify vehicles ahead for tracking]
«refersTo»
ACCV! {lane}
«designedDomain»
IVAS
«DesignedDomain»
description=Identified vehicles ahead on same lane
ACC! {speed, distance of VA on same lane}
«constrains»
IVAS! {speed, distance of VA on same lane}

Figure 12: Essential problem diagram for R-3.

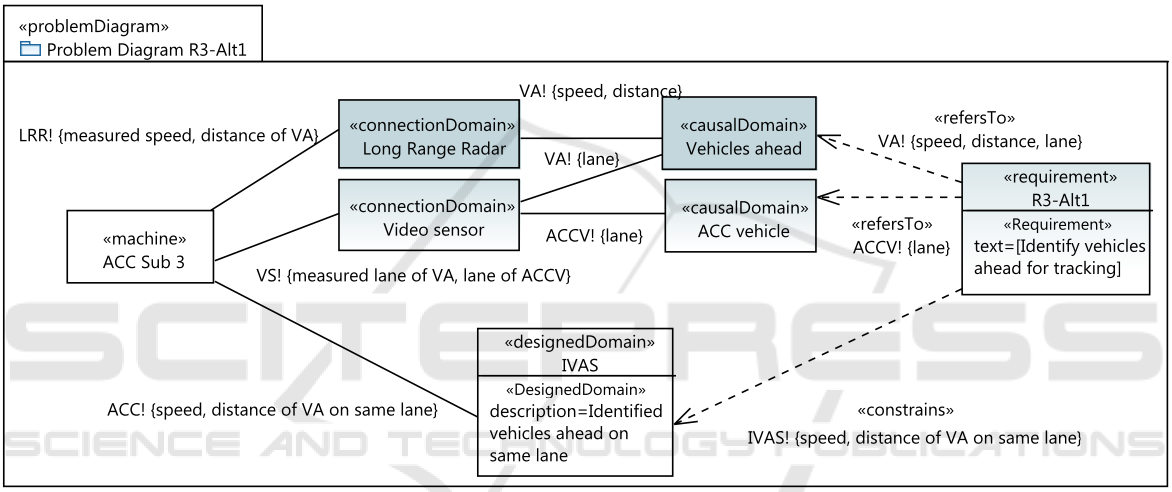


Figure 13: Incarnation problem diagram for R3-Alt1.

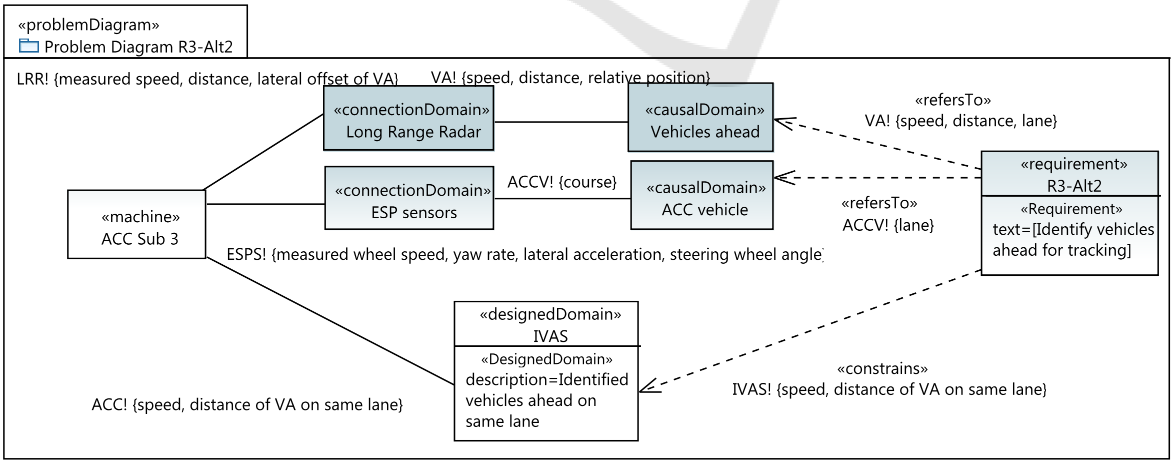

«problemDiagram»
Problem Diagram R3-Alt2
LRR! {measured speed, distance, lateral offset of VA}
VA! {speed, distance, relative position}
«connectionDomain»
Long Range Radar
«causalDomain»
Vehicles ahead
«refersTo»
VA! {speed, distance, lane}
«connectionDomain»
ESP sensors
ACCV! {course}
«causalDomain»
ACC vehicle
«requirement»
R3-Alt2
«Requirement»
text=[Identify vehicles ahead for tracking]
«machine»
ACC Sub 3
«refersTo»
ACCV! {lane}
ESPS! {measured wheel speed, yaw rate, lateral acceleration, steering wheel angle}
«designedDomain»
IVAS
«DesignedDomain»
description=Identified vehicles ahead on same lane
ACC! {speed, distance of VA on same lane}
«constrains»
IVAS! {speed, distance of VA on same lane}

Figure 14: Incarnation problem diagram for R3-Alt2.

The essential problem diagram for R-3 is shown in Figure 12. One peculiarity in Figure 12 is that we introduced a designed domain called IVAS (identified vehicles ahead on same lane). IVAS is a so called

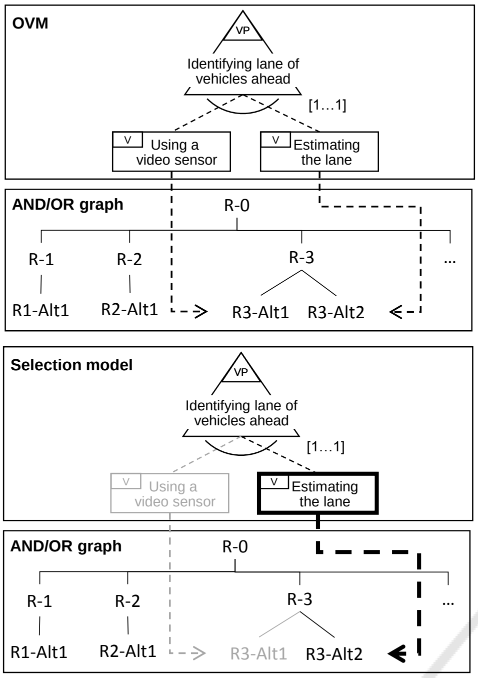
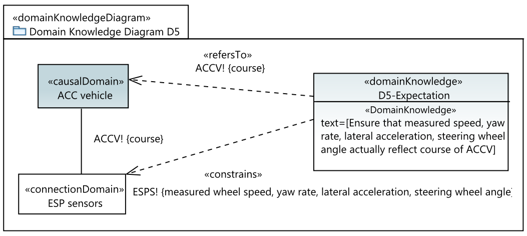


Figure 15: Part of the OVM for the ACC Software.

designed domain, i.e. it is actually part of the machine ACC Sub 3. Based on the information ACC Sub 3 gets, it decides whether detected vehicles ahead are on the same lane or not. The ones that are on the same lane are stored by ACC Sub 3.

Step 3: Create Incarnation Problem Diagrams. Examples of incarnation problem diagrams are given in Figures 13 and 14. These are two possible incarnations for the essential requirement R-3 (shown in Figure 12). Alternative 2 represents the ACC system as described in the introduction using ESP sensors and the long range radar to identify vehicles ahead for tracking. In Alternative 1, in contrast, the long range radar is used together with a stereo video sensor for the same purpose. In case of Alternative 1, the lane of vehicles ahead is identified precisely, while it is only estimated in case of Alternative 2. The *r* and *d* variables (at the requirement reference and the constraining reference) in Figure 13 and Figure 14 are the same, while the *m*, *i*, *c*, *o* variables at the interfaces are different.

Step 4: Select Alternatives and Derive Concrete Model. Figure 15 depicts an excerpt of the OVM with the artefact dependencies (shown as dashed arrows) to the AND/OR graph as well as a selection model and the derived AND/OR graph. In the selection model and the derived AND/OR graph, the alternatives that are not selected are shown in grey (R3-Alt1) while the selections are emphasized (R3-Alt2).



text=[Ensure that measured speed, yaw rate, lateral acceleration, steering wheel angle actually reflect course of ACCV]

ESPS! {measured wheel speed, yaw rate, lateral acceleration, steering wheel angle

Figure 16: Example of a domain knowledge diagram.

Step 5: Make Expectations and Domain Hypotheses Explicit. An example of a domain knowledge diagram (created by instantiating Frame 2) is given in Figure 16. It shows the expectation we, as developers of the ACC software have, regarding the ESP sensors shown in Figure 14. This expectation is to be satisfied by developers of the ESP sensors. We expect that the wheel speed, yaw rate, lateral acceleration, and steering wheel angle measured by the ESP sensors actually reflect the course of the ACC vehicle. Therefore, the ESP sensors are constrained in the domain knowledge diagram in Figure 16, while the ACC vehicle is referenced.

4.4 Benefit

The documentation that is created when applying our method enables developers to analyse the impact of contextual changes systematically and to integrate changes in a consistent manner. For example, if the ACC software shall actually be reused in another vehicle that is additionally equipped with a video sensor, the developers can see in the documentation what the current *r* is in the problem diagram for R-3 (identifying vehicles ahead) and how it is realized (*m* and *i*). In the OVM, they can even see that there was a decision point regarding lane identification and that a video sensor was even considered as an alternative. As another example consider the case in which other developers tell us that they are not able to provide the input variable *i* we expected from them but a slightly different one. Based on the documentation, we are able to trace back to which *r* this variable contributed and whether there are other alternatives to achieve *r*.

5 RELATED WORK

Jackson discusses the Four-Variable Model in his book (Jackson, 2001) as well. He depicts the Four-Variable Model as a problem diagram which is shown in Figure 17. The machine is a control machine which uses sensors and actuators to monitor/control the environment. The four variables are annotated at the interfaces between machine, sensors/actuators, and environment. The constraining reference (which is at the same time also a requirement reference) is annotated with the *m* and *c* variables which means that the requirement REQ refers to the variable *m* and constrains the variable *c* of the environment.

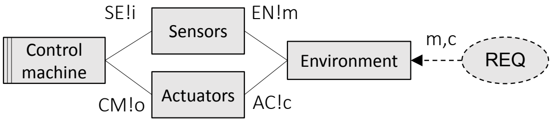


Figure 17: Four Variable Model as problem diagram. (Jackson, 2001).

Jackson is of the opinion that the quantities at the constraining reference are *m* and *c*, i.e. they represent the same quantities as the ones that are monitored/controlled by the sensors/actuators (annotated at the interface between sensors/actuators and environment). This is different to our Six-Variable model. As we pointed out in Section 3, we think that the monitored/controlled quantities are often different than the ones mentioned in the requirement (the *r* and *d* variables).

Gunter et al. (Gunter et al., 2000) differentiate between four types of phenomena: e_h are environmental phenomena hidden from the system, e_v are environmental phenomena visible to the system, s_v are system phenomena visible to the environment, and s_h are system phenomena hidden from the environment. According to Gunter et al., e_v correspond to the monitored variables in the Four-Variable Model and s_v to the controlled variables. The s_h phenomena contain the input and output variables. However, according to Gunter et al., there are no e_h phenomena in the Four-Variable Model. e_h corresponds to the *r* and *d* variables in our Six-Variable Model. Yet, the benefit of our method is that we differentiate between the *r* and *d* variables and provide guidance in identifying them.

There are three further approaches that extend the Four-Variable Model. Yet, their extensions focus on the system and are directed towards the machine, while our extension is directed towards the environment/real world (i.e. the opposite direction). Nevertheless, we explain them shortly. First, Bharadwaj and Heitmeyer (Bharadwaj and Heitmeyer, 1999) suggest to specify the required behaviour of the machine in terms of the following three modules: an input device interface module, a device-independent module, and an output device interface module. The input device interface module specifies how the input variables provided by the sensors are to be used to compute estimates of the monitored variables. The device-independent module specifies how the estimated monitored variables are to be used to compute estimates of the controlled variables. The output device interface module finally specifies how the estimates of the controlled variables are used to compute the output variables that drive the actuators. Thus, the focus of this approach is mainly on the machine and its input and output variables. The second approach is the one of Miller and Tribble (Miller and Tribble, 2001). They propose an extension of the Four-Variable Model that clarifies how system requirements can be allocated between hardware and software. So the focus of their extension is on the system while our extension is directed towards the environment. The third approach is the one of Patcas et al. (Patcas et al., 2013). They criticise that the Four-Variable Model does not specify the software requirements, but bounds them by specifying the system requirements and the input and output hardware interfaces of the system. It is the software engineers task to develop a software that satisfies the system requirements and hardware interfacing constraints. To ameliorate this situation, the authors formalize the properties of acceptable system and software implementations and provide a necessary and sufficient condition for the existence of an acceptable software implementation. Beyond that, the authors provide a mathematical characterization of the software requirements in terms of their weakest specification. Again, the focus of this work is on the software/machine and its interfaces. Since the focus of these three approaches is on the system, they can theoretically be combined with our Six-Variable Model. We will analyse that in future work.

Another work that is related to our context modelling method is van Lamsweerde's goal-oriented requirements engineering method (van Lamsweerde, 2009). He assumes Jackson's model of the world and the machine and suggests a goal-oriented method. Multi-agent goals are refined (in AND-refinement trees) until the subgoals can be assigned to single agents in the environment (then they are expectations) or to agents in the system (then they are requirements). Leaf nodes may also be domain hypotheses or domain properties. For the system agents, agent models are created. For expectations, no further models are created. Van Lamsweerde's work has similarities with our context modelling method, since we use AND/OR graphs and his differentiation between expectation and domain hypotheses. Yet, our context modelling method is based on the Six-Variable Model, i.e. we document the six variables, while he documents only the classical four variables. Furthermore, he does not document contextual decisions and the options that were selectable.

6 CONCLUSION AND FUTURE WORK

Contextual decisions need to be documented because they might change the environmental quantities that are relevant for a software. After decision making, another set of quantities is frequently relevant than before. Without guidance, developers tend to document only the environmental quantities that are relevant after decision making (i.e. the classical four variables). Yet, these quantities restrict *R* (the set of requirements) unnecessarily to one possible context although *R* actually allows many more contexts. Our method supports the documentation of both, the environmental quantities that are relevant before and after decision making, namely the six variables. Furthermore, it ensures traceability of contextual decisions that are made. This facilitates later reuse of the developed software.

In future work, we plan to apply our method to further, more complex examples, also in other domains (e.g. a patient monitoring system as part of ambient assisted living in the health domain). We also consider a comparative evaluation with student groups to compare our Six-Variable Model with the approach suggested by Gunter et al. (Gunter et al., 2000).

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