Abstract

Discovering and documenting potential failures and irregular user behavior that can interrupt the normal system behaviour is very important during the development of critical systems. Failure Mode and Effects Analysis (FMEA) is a bottom-up inductive analysis method that helps to identify potential failure modes based on experience with similar products and processes. Model-Driven Development (MDD) is a software development paradigm that raises the level of abstraction of software development by changing the focus from code to models and automating the generation of code from models. MDD also eases the derivation of analysis models for different software non-functional properties (NFPs) in the early stage of software development.

The objective of this thesis is to develop a model transformation process that takes as input a UML software model with failure mode annotations and generates a FMEA model. The transformation is developed in Epsilon, a new family of languages specialized in model transformations, refinement and management.
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>Al</td>
<td>Alarm</td>
</tr>
<tr>
<td>ATL</td>
<td>Atlas Transformation Language</td>
</tr>
<tr>
<td>DSM</td>
<td>Domain-Specific Model</td>
</tr>
<tr>
<td>DSML</td>
<td>Domain-Specific Modeling Languages</td>
</tr>
<tr>
<td>EMF</td>
<td>Eclipse Modeling Framework</td>
</tr>
<tr>
<td>EOL</td>
<td>Epsilon Object Language</td>
</tr>
<tr>
<td>Epsilon</td>
<td>Extensible Platform of Integrated Languages for mOdel maNagement</td>
</tr>
<tr>
<td>ETL</td>
<td>Epsilon Transformation Language</td>
</tr>
<tr>
<td>FMEA</td>
<td>Failure Mode and Effect Analysis</td>
</tr>
<tr>
<td>FMECA</td>
<td>Failure Mode Effect and Critical Analysis</td>
</tr>
<tr>
<td>Ev1</td>
<td>Electrovalve 1</td>
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<td>FTA</td>
<td>Fault Tree Analysis</td>
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<td>HAZOP</td>
<td>Hazard and Operability</td>
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<tr>
<td>ISR</td>
<td>Interrupt Service Routine</td>
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<tr>
<td>LCS</td>
<td>Level Control System</td>
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<tr>
<td>MDA</td>
<td>Model Driven Architecture</td>
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<tr>
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<td>Model Driven Development</td>
</tr>
<tr>
<td>MDE</td>
<td>Model Driven Engineering</td>
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<tr>
<td>MOF</td>
<td>Meta-Object Facility</td>
</tr>
<tr>
<td>Mv1</td>
<td>Mechanical Valves1</td>
</tr>
<tr>
<td>NFP</td>
<td>Non-Functional Property</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>OCL</td>
<td>Object Constraint Language</td>
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<tr>
<td>OMG</td>
<td>Object Management Group</td>
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<tr>
<td>PIM</td>
<td>Platform-Independent Model</td>
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<td>Platform-Specific Model</td>
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<td>Query/View/Transformations</td>
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<td>Real-Time Embedded Systems</td>
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<td>Level Sensor 1</td>
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<td>Tele-echography</td>
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<tr>
<td>UML</td>
<td>Unifying modeling language</td>
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<tr>
<td>XMI</td>
<td>XML Metadata Interchange</td>
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<tr>
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<td>Extensible Markup Language</td>
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<tr>
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<td>Extensible Stylesheet Language Transformation</td>
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1 Chapter: Introduction

1.1 Motivation and Objectives

The application of sophisticated computer systems built for high risk tasks is on the rise in different domains such as military, automotive, aerospace, health care, financial, etc. The consequences of failures in such systems maybe very costly and severe, and can lead to loss, physical damages or casualties. Therefore, proper development methods of dependable and safe systems are extremely important. In [PET95] are discussed a number of software failures. In [CHA05] it is given a good summary of software failure and their cost from 1992 to 2005 (Sources: Business Week, CEO Magazine, Computerworld, Info Week, Fortune, The New York Times, Time, and The Wall Street Journal). For instance, it shows how in 1996 software specification and design errors in ArianeSpace (France) program caused the explosion of a $350 million Ariane 5 rocket. This could have been avoided if all necessary verification and validation of reliability, safety and other functional and non-functional requirements would have been properly done. This is one of the reasons why it is of high interest to conduct research in the area of automating some of the engineering safety tools for software development.

According to [MHE16]: “Safety analysis has the objective to assess system safety during design phase and ensure that the designed systems have satisfactory safety level”. In accordance with NASA Standard on software safety, risk is defined in [HAS05] as a “function of the anticipated frequency of occurrence of an undesired event, the potential severity of resulting consequences, and the uncertainties associated with the frequency and severity”. FMEA (Failure Mode and Effect Analysis) is defined in [YU11] as a
powerful and effective engineering tool for the analysis of all possible failure modes and the elimination of the potential failure.

The term Model-Driven Development (MDD) refers to a software development paradigm whose main focus is to raise the level of abstraction of software development by changing the focus from code to models, as well as to automate the code generation from models. This thesis work is based on MDD, using some of the techniques, languages and tools that support MDD. Another important merit of MDD, apart from automatic code generation, is to facilitate the derivation of formal analysis models for the verification and validation of non-functional properties (NFP), such as safety, performance, reliability, availability, scalability, security, etc. The NFP verification/validation adds more engineering aspects to the software development process, which is a step forward from the Model-Driven Development to the Model-Driven Engineering paradigm.

In order to analyze a certain NFP in the MDE context, the following steps can be followed: a) the addition of NPF-specific information to the software model with the help of specific profiles, b) the execution of a pre-defined model transformation to generate an analysis model for the given NFP, followed by c) the analysis of the generated model using an existing solver, and finally d) giving feedback to the model designer. For instance, these steps were followed to transform annotated Unified Modelling Language (UML) models to Fault trees in [ZHA14] and to Layered Queueing Networks in [ZAR16]. UML is a general-purpose object-oriented visual modelling language that offers numerous formalisms to allow developers to create models during all phases of the development life cycle [MUS09].
This thesis work is at the intersection of the following disciplines: software engineering, model-driven development and safety analysis. The thesis focuses on addressing system safety during the software development process with the use of a known safety analysis method called Failure Mode and Effect Analysis (FMEA). More specifically, the thesis develops an approach for transforming a UML software model consisting of composite structure diagram and sequence diagram annotated with safety information into an FMEA model, which in turn will be transformed into the usual FMEA table (textual) form defined in the literature.

![Diagram](image)

**Figure 1-1 Activities for the proposed transformation**

Figure 1-1, shows the activities necessary to transform an UML annotated with Fmode profile to an FMEA table. The UML modeling tool used for creating UML models is Papyrus [PAP15], which is an open-source tool based on Eclipse modeling framework (EMF). There are two preliminary steps performed in the thesis: the definition of the FMEA Metamodel using the language Emphatic [EMF15] and the definition of the Fmode profile. The input UML model conforms to the UML 2.5 Metamodel standardized by OMG. The transformation implemented in ETL generates the target FMEA model in
XML format. The XML document of the automatically generated FMEA model is then processed with XSLT to produce the corresponding FMEA table in text format, which will be presented to the developer.

1.2 Thesis Contributions

The main high-level goal of this thesis is to contribute to the integration of software safety analysis into the model-driven software development process. The first major objective of the thesis is to develop a model transformation process that accepts as input a UML software model with safety annotations, and generates a corresponding Failure Mode and Effect Analysis (FMEA) table as output. Other objective of the thesis is to use Epsilon, a new family of model transformation languages. To achieve the objectives mentioned above, the following contributions were made:

i. Development of an automatic multi-step FMEA model derivation process, which starts with a UML software model extended with the Fmode profile and generates the corresponding FMEA model in XML format, which is in then transformed into a textual format.

ii. The definition of the FMEA target metamodel expressed in the Emphatic language (presented in chapter 3).

iii. The definition of the Fmode profile for failure mode extensions to UML models (presented in chapter 3).

iv. The design and implementation of the model transformation: mapping of UML+Fmode model elements to corresponding FMEA model elements and designing and implementing a model transformation composed of ETL rules and
operations, which work together to generate the target FMEA model (presented in chapter 4).

v. Verification and validation of the ETL transformation. All the test cases and the running example used in the thesis for verification and the two case studies from literature used for validation are presented in chapter 5 and 3, respectively.

vi. Finally, since FMEA is usually presented in a tabular form (spreadsheet) a Text-to-Text transformation using XSLT to transform the generated FMEA model in XML format to its table format equivalent is presented in chapter 3.

1.3 Thesis Contents

This thesis consists of 6 chapters, including this introductory chapter, and an appendix. Chapter 2 introduces the background material required for this work, which includes a basic general description of software modeling languages, Model-Driven Development, Model-Driven Architecture (MDA), a brief description of UML and its major elements used in this thesis, an introduction to model transformation, the transformation languages we used in this work, description of some features of Software safety analysis and some engineering safety analysis tools with more attention to FMEA as a safety analysis tool. Also, some related works from literature on FMEA using some kind of model transformation are summarized.

Chapter 3 describes the design of the transformation process from annotated UML to FMEA model generation. It contains a detailed description of both metamodels of the source and target models with a running example.
Chapter 4 explains the main mappings from UML+FMode models to FMEA models. The mapping rules of the transformation are presented separately with the rules and operations.

Chapter 5 presents six test cases created by the author and two complete case studies from literature, in which all the main aspects of this model transformation were verified. Chapter 6 is the conclusion that presents the main thesis accomplishments alongside with the limitations and some possible areas for future work.
2 Chapter: Background and State of the Art

2.1 Software Modeling Languages

In [GRO09] modeling is described as an integral part of complex software system development projects, whose main aim ranges from assisting developers and customers to communicate with each other, test case generation or automatic derivation of the developed system code. A modeling language can be defined as a language used to express the structure and behavior of systems, information or abstract knowledge, following a set of guiding rules. A complete definition of a modeling language consists of the description of its syntax, including well-formedness rules and its semantics [HAR04]. A well-known example of modeling language is the Unified Modeling Language (UML), whose goal is to represents software during the development process. According to its founders, UML is a graphical language for visualizing, specifying, constructing and documenting the artifacts of software-intensive system [BRJ01]. UML is standardized by the Object Management Group (OMG) [UML15] and is widely used in research and industry. UML is the modeling language used in this thesis for representing software systems.

Model and Metamodel

According to [ISO12], models describe the structural dimension of an object model and specify the collaborations among the objects. Structural models are used in conjunction with dynamic modeling techniques representing behavior, such as those based on finite state machines.

A metamodel is a special kind of model that defines the abstract syntax of a modeling language. The abstract syntax defines the set of modeling concepts expressed in the
language, their attributes and their relationships, as well as the rules for combining these concepts to construct partial or complete models. The UML metamodel used in the thesis is the standard specification adopted by OMG [UML15]. Another metamodel used in the thesis is the FMEA metamodel; its definition given in the next chapter was inspired from [TAGU11].

**Model Driven Development (MDD)**

MDD is a software development paradigm based on the idea of modelling. MDD is shifting the primary development focus from code (i.e., usual computer programming syntax and semantics) to models, thereby raising the abstraction level of the software development activities. MDD is characterized by automatic code generation from models. One of the advantages of MDD is the use of models that are very close to the problem domain, which has proven to make it easier to specify, understand, and maintain models [SEL03]. Also, the use of models provides easy means for verifying the model’s non-functional properties, such as reliability, availability, safety, performance, scalability etc.

**Model Driven Architecture (MDA)**

Released in 2001, MDA is OMG’s vision for model-driven development based on OMG standards; a more detailed presentation of the MDA definition was adopted by OMG in 2003 [MDA03]. One major aim of the MDA framework is the separation between the platform-independent specification of the software system and the platform-specific implementation of the system. This approach facilitates portability between different platforms and model reuse.

**Model Driven Engineering (MDE)**

Model Driven Engineering (MDE) includes Model-Driven Development (MDD), but also
extends the use of models to a wider range of uses, as presented below. MDE makes it easy to consider models as the key artifact of the software engineering process [SEL03]. Complex systems can now be easily modeled and presented, but in recent time modeling has gone beyond mere presentation and documentation and can be used for the following engineering purposes:

i) Model Testing: Detection of errors at the model level is made easier with the provision of testing facilities at a very high level of abstraction. Unlike testing at the code level, which is very detailed, so error detection and elimination is not as easy.

ii) Documentation: With the consistent increase in the complexity level of software systems with modern technologies, comprehensive detailed documentation has become an important aspect of engineering work. Proper modeling of the system has proven to be a capable option for the system’s detailed specifications and comprehensive documentation.

iii) Code generation: Automatic or semi-automatic code generation of programming code is a vital and very important aspect of the model-driven approach (Model2Text transformation). Code can be automatically generated from the models, making the modeling more useful and not limited to just communication purposes.

iv) Verification of non-functional properties: Software models can be transformed into analysis models that can also, be expressed in different formats. Like in the case of this thesis, we developed a transformation from UML to FMEA model for safety analysis. Other modeling techniques for safety analysis are HAZOP, Fault
Model transformation: Models may have different purposes and application domains, different levels of abstractions and can be defined in different languages. The basic aim of a model transformation is to automatically transform a certain kind of model into another kind of model. Recently, specialized languages for model transformations have been defined and tool support has been developed, as described in section 2.2.

2.1.1 Unified Modeling Language (UML)

The Unified Modeling language (UML) standardized by Object Management Group (OMG) [UML15] is a general-purpose software modeling language used during the analysis, design, implementation, code generation, testing and maintenance phases of software systems by human users. The UML metamodel is defined in turn by using the Metal Object Facility (MOF) language [MOF11]. UML supports a set of graphical notations representing its concrete syntax, defined informally in the OMG standard specification [UML15].

UML provides fourteen different diagram types, which represent different perspectives of the system under development. Usually UML modeling tools are used to create UML models composed of multiple diagrams. Papyrus is the UML tool (editor) used in this thesis [Papy15]. Basically the UML diagrams are classified into two broad categories: structure diagrams and behavior diagrams. A structural diagram is used to describe the system’s structure, as shown later in this thesis with the use of Composite structure diagram for the running example and the case study systems. The UML structure diagram category includes: Class diagram, Object diagram, Package diagram, Component
diagram, Deployment diagram, Composite structure diagram and Profile diagram. On the other hand, the behavior diagrams describe the interactions between structural entities and/or the behavior of a system, subsystem or component. The UML behavior diagram category includes: Use Case diagram, State Chart, Activity diagram and Interaction diagram, which in turn can be a Sequence diagram, Timing diagram, Communication diagram, and Interaction overview diagram. In this thesis, the Composite structure diagram is used to represent the system structure and the sequence diagram to represent the system behavior. (Both the Composite structure and Sequence diagrams are described in more detail below, as they are used in the transformation rules defined in Chapter 4).

**UML metamodel**

As described above, a metamodel is a model describing the abstract syntax and well-formedness rules of a modeling language. In other words, the UML metamodel describes the UML model elements, their attributes and relationships [UML15]. The metamodel is specified in the MOF language [MOF11] and it is organized in packages. The MOF language is aligned with UML, in the sense that MOF is composed of a subset of UML concepts used for modeling classes and packages. A UML model is an instance of the UML metamodel. In the rest of this subsection are presented the metamodel fragments for UML Composite Structure, Interaction and Profile, which are used for writing the transformation from UML to FMEA presented in Chapter 4.

**UML Composite Structure diagram**

A StructuredClassifier is a structural concept that may have an internal structure of Connectable Elements (each playing a given role) and an external structure of one or more Ports. The connectable elements can themselves be instances of a
StructuredClassifier, allowing for nested structures). The Ports act as local agents of remote collaborators which interact with the Structured Classifier owning the ports, allowing us to model the overall behavior (i.e., the interactions of this classifier with other parts of a system [ZHA14]). In this thesis, the composite structure diagram is used to represent the system structure, which may contain software components and hardware components. Figure 2-1 describes the abstract syntax of a UML StructuredClassifier, which owns any number of attributes representing the parts and any number of connectors that link the parts with each other. An attribute is modeled by a Property metaclass, which in turn is a Connectable Element (an abstract class representing the internal roles in the StructuredClassifier [UML15].

![Figure 2-1 The UML2.5 Structural Classifier Metamodel [UML15]](image)

**UML Sequence Diagram**

The UML Sequence diagram is the most common kind of UML Interaction Diagram that focuses on the interchange of Messages between the model’s Lifelines. More specifically,
a sequence diagram describes an interaction by showing the sequence of Messages that are exchanged between the interaction participants (represented by Lifelines), along with their corresponding OccurrenceSpecifications on the Lifelines. Figure-2-2 shows the Lifeline metamodel fragment from [UML15]. In this thesis, Sequence diagrams are used to capture the message exchange or signal passing between components, emphasizing the elements that may fail during the component interaction.

Figure 2-2 The Lifeline metamodel [UML15]

**UML Profile**

An important flexibility embedded in UML is the provision of a set of extension mechanisms (profiles) to accommodate the modeling of some domains for which the UML notation should be specialized. UML profile definition allows the customization and extension of its own syntax and semantics in order to adapt it to certain application
domains [FUE04]. As defined by UML 2.5 Standard, a Profile “is a restricted form of metamodel that can be used to extend UML”.

The primary UML extension construct is the Stereotype, which may have a number of Properties (representing attributes) and Constraints. Stereotypes are used to extend one or more UML metaclasses with properties and constraints that are characteristic to a certain domain. Figure3-2 shows the metamodel of a UML profile. A UML Profile is defined as a UML package with the keyword «profile» that groups together related stereotype definitions, their attributes and constraints. The application of a profile to a model should not change that model in any way but merely define a view of the extended model [UML15].

![UML Profile metamodel](image)

**Figure 2-3 UML Profile metamodel [UML15]**

A stereotype is a class that defines how an existing metaclass (or other stereotype) may be extended, and enables the use of platform or domain specific terminology in addition
to the standard UML notation. Certain stereotypes are predefined in the UML, others may be user defined.

UML Profiles can be used to define Domain Specific Modeling Languages based on UML extensions. According to the definition provided in [AMY06] “Domain-Specific Modeling Languages (DSMLs) are high-level languages specific to a particular application or set of tasks. They are closer to the problem domain and concepts than general-purpose programming languages. Improvements in productivity and comprehensibility are often cited as benefits.”

Using UML profiles provides the additional advantage that the extended models can be processed with standard UML editors, without any need to change the tools, as profiles are standard mechanisms for extending UML models [PETR13].

In this thesis we define a profile that allows us to add failure mode annotations to the UML source model. These annotations are processed by the transformation developed in the thesis.

2.2 Model transformations

A model transformation is a special application that takes one or more input models (each defined by a source metamodel), and generates one or more output models (each defined by a target metamodel). Figure 2-1 illustrates the relationships between the models and metamodels involved in a model transformation. Model transformations may either be of the type of model-to-model (M2M) or model-to-text (M2T) transformation. The choice of what type of transformation to use is dependent on the main purpose of the transformation. In this thesis we use both M2M and M2T transformations.
Model-to-Model (M2M)

This is the type of transformation used in this thesis to transform an annotated UML model to the corresponding FMEA model, where the input and the generated output are both models. M2M is a very convenient way of transforming Platform-Independent-models (PIM) to Platform-Specific-Models (PSM), or like in the case of this thesis transforming an annotated software model to an analysis model for a given non-functional property (safety in this case).

Model-to-Text (M2T)

M2T is the form of model transformation, which generates textual artefacts from models. In this type of transformation, the input is a model while the generated output is a text artefact or an application code.
2.2.1 Specialized model transformation languages

Not long ago, model transformations had usually been carried out by using general-purpose programming languages [ZHA14], especially Java which is used in the open-source Eclipse Modeling Framework. However, more recently the development of specialized model transformation languages has become a major aid in model-to-model transformation. Special model transformation languages advantages include it syntax that provide easy access to the model elements and allows expressing constraints in the Object Constraint Language (OCL) style.

Model transformation languages are classified into three different categories: declarative, imperative and hybrid.

**Declarative transformation languages** provide a very good and solid transformation aid where both the source and target metamodels are of similar structure, by providing a model to model mapping of the two metamodels, though declarative transformation seems to provide a very good mapping ground for model transformation, it is limited in the cases where complex mapping is required.

**Imperative transformation languages** on the other hand, are transformation language, which is capable of supporting more complex transformation cases but operate at a much lower level of abstraction.

**Hybrid transformation languages** were developed to take care of the limitations of both purely declarative and purely imperative languages.

Examples of transformation languages include; ETL, QVT, ATL, MOF, JTL, GReA, etc.
2.2.2 Query/View/Transformation (QVT)

QVT is a modeling language standardized by OMG standard with more concentration on model transformation, view and query as the name implies. OMG issued a Request for Proposal (RFP) in 2002 on MOF Query/View/Transformations to develop a standard transformation language with OMG standards compatibility, QVT standard language evolved out of this proposal [QTV11]. The QVT aids two levels of declarative language; the Relations and the Core, it also supports an imperative language; the Operational mapping. The Relations language is basically employed in the matching of object patterns, creating object templates and tracing of model elements, while Core language on the other hand, seems to be much simpler and easier compare to the Relations language, it is used for matching patterns with a variable sets evaluated against a set of models. Operational mappings language this language is usually applied when invoking the transformation imperative representations from the declarative language.

2.2.3 Atlas Transformation Language (ATL)

ATL is another model transformation languages proposed during the OMG standardization process. It was released earlier compared to QVT, so it had quite a number of user of its toolset [ATL12]. ATL is hybrid, having both declarative and imperative characteristics. An ATL program is composed of different rules describing the matching/mapping and navigation of source model elements to generate the target model elements.

2.2.4 Epsilon family of languages

Epsilon (Extensible Platform of Integrated Languages for mOdel maNagement) is a family of consistent and interoperable task-specific languages, designed to handle model
management tasks such as model transformation, code generation, model comparison, merging, refactoring and validation [KOL15]. The Epsilon family framework contains Epsilon Object Language (EOL), Epsilon Transformation Language (ETL), Epsilon Wizard Language (EWL), Epsilon Merging Language (EML), Epsilon Validation Language (EVL), Epsilon Generation Language (EGL), and Epsilon Comparison Language (ECL).

In this thesis we used the Epsilon Transformation Language (ETL) for the M2M transformation from UML to FMEA. ETL is a hybrid transformation language used for model-to-model transformation in the Epsilon family. ETL also possess the EOL imperative features for proper handling of complex model transformation. ETL is capable of expressing the transformation at a higher level of abstraction than a general-purpose language such as Java. ETL accepts an arbitrary number of input models and generates an arbitrary number of output models [KOL15].

2.3  Software Safety Analysis

Software system safety engineering application focus more on an effective system level hazard analysis process.

2.3.1  Dependability Analysis

Dependability is a nonfunctional property (NFP) of a system, defined in [AVIZ04] as the ability to avoid failures that are more frequent and severe than acceptable. Dependability covers a set of attributes: availability (readiness for correct service), reliability (continuity of correct service), safety (absence of catastrophic consequences for the users and the environment), integrity (absence of improper system alterations) and maintainability
(ability to undergo modification and repairs). The evaluation of the dependability attributes can be done with quantitative and/or qualitative methods [LYU96]. Quantitative tools can be used to measure both system Availability and Reliability attributes, while the other safety attributes are more subjective. For instance, in the case of system safety it may not be easily determined using a particular measurement what is the system safety confidence level, unlike the case of system reliability, which can be determined using quantitative measures as failures over time.

Three concepts are important for dependability analysis: fault, error and failure. *Fault* can be defined as a system defect which can either result into a system error or not; system *error* is propagation from system fault, while system *failure* represents an instance in time when a system’s behavior is contrary to its defined specifications. When a fault is activated, can result to an error (system invalid state) and the system’s invalid state propagates to become an error which may in turn lead to another system failure (a vivid and observable deviation of the system from its specifications) or another system error. According to the NASA standard [NAS04] failure is “non-performance or incorrect performance of an intended function of a product. A failure is often the manifestation of one or more faults”.

### 2.3.2 Safety Analysis Methods

System safety analysis methods include the following:

- Fault Tree Analysis (FTA) is a deductive, top-down method safety analysis method with the focus on analyzing effects of the initiating faults and events on a system.
• Failure Mode and Effects Analysis (FMEA) is a bottom-up, inductive analysis method with the main focus on analyzing the effects of a single component failure on subsystems or system [GSF96].

• Failure Mode, Effect and Critical Analysis (FMECA) is an extension of FMEA which is also, a bottom-up, inductive system safety analytical method. It extends FMEA with its analysis concentration on the system’s components with high risk criticality, which is then used as a base to draw the probability of failure modes against the severity of their consequences. The components with relatively high failure modes occurrence and high severity level are given more attention with remedial effort. Mil-Std 1629 (ships), “Procedures For Performing a Failure Mode, Effects and Criticality Analysis” [USM74] was published in 1974. FMECA seems to be of greater importance in safety critical fields such as Military, Medicine (health), Aeronautics, Automobile, space and North Atlantic Treaty Organization (NATO) military applications etc.

• Dependence diagram (DD) known as reliability block diagram (RBD) and Markov analysis. It is equivalent to a success tree analysis (STA) with the logical inverse of an FTA, and it depicts the system using paths rather than gates. DD and STA produce probability of success instead of probability of failure.

• Hazard and Operability study (HAZOP) is a qualitative technique based on breaking down a complex design process into a number of smaller and simple sections (nodes), which are then reviewed individually, to identify and evaluate any associated risk to personnel or equipment.
The two most commonly used safety analysis techniques are FMEA and FTA. As indicated before, this thesis focuses on FMEA.

2.3.3 Failure Mode and Effects Analysis (FMEA)

FMEA history can be traced back to its initial development in the late 1940s by the US military to study failure classification. Examples of very important projects in which FMEA was used in the 1960s were the Apollo space missions. Another major use of FMEA as a tool was by Ford Motors in the 1980s with the focus on risks reduction in their automobile production.

FMEA is a technique for assessing the dependability of system’s components and the system safety. FMEA has been used with success in the process industry in support of safety and reliability. Some of the advantages of FMEA is that it is easy to understand, can decrease cost, permit reduction of the development time and increase customer satisfaction. According to the definition given in [DEL04] FMEA is an engineering analytical technique that has proven to be domain independent (it has been used in diverse field of engineering) for identification and reduction of hazards in designing, manufacturing and maintenance of systems. The analyses enhance the complete/exhaustive analysis of all the system’s components or its sub-systems to determine all the potential failure modes and its effects on the entire system stability [SPA03].

There are four common categories of FMEA: a) system FMEA class, b) design FMEA class, c) process FMEA class and e) machinery FMEA class. These categories of FMEA focus on different levels of analysis, according to the classes. System FMEA class focuses more on potential failure in the system level interactions, the design FMEA class
has its main focus on potential failure of product design, the process FMEA class analyzes potential failure in the process that produces/makes the product, and the machinery FMEA class is used to analyze the potential failure in the machinery that performs the process [MOR11]. FMEA is generically created within spreadsheets manually with a set of participants, which could include but are not limited to the following: designers, customers, owners, suppliers, etc.

FMEA usually involves the following steps:

- Determine the participants
- Brain storming using Murphy’s law (“Anything that can go wrong will go wrong”). Identify all components to be analyzed, the system and subsystems, all processes, functions (all conditions that could fail to meet required level of quality and reliability). The team must have the ability to describe the failure cause and its effects both local and propagated effect on the system.
- Criteria for FMEA analysis are based on the following failure characteristics: Severity, Occurrence frequency and Detection method.

The following ranking (defined as an enumeration type) were used in this thesis similar to [MRAZ05]:

---

37
### Table 2-1 Severity Ranking and suggested criteria

<table>
<thead>
<tr>
<th>Effect</th>
<th>Criteria</th>
<th>Severity</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>No Effect</td>
<td>A portion of the product may have to be reworked. Defect not noticed by average customers; cosmetic defects.</td>
<td>1</td>
</tr>
<tr>
<td>Very Minor</td>
<td>Minor disruption to production line.</td>
<td>A portion of the product may have to be reworked. Defect noticed by average customers; cosmetic defects.</td>
<td>2</td>
</tr>
<tr>
<td>Minor</td>
<td>Minor disruption to production line.</td>
<td>The product may have to be sorted and reworked. Defect noticed by average customers; cosmetic defects.</td>
<td>3</td>
</tr>
<tr>
<td>Very Low</td>
<td>Minor disruption to production line.</td>
<td>100% of product may have to be reworked. Customer has some dissatisfaction. Item is fit for purpose but may have reduced levels of performance.</td>
<td>4</td>
</tr>
<tr>
<td>Low</td>
<td>Some disruption to production line.</td>
<td>A portion of the product may have to be scrapped. Customer has some dissatisfaction. Item is fit for purpose but may have reduced levels of performance.</td>
<td>5</td>
</tr>
<tr>
<td>Moderate</td>
<td>Some disruption to production line.</td>
<td>Product may have to be sorted and a portion scrapped. Customer dissatisfied. Item is useable but at reduced levels of performance.</td>
<td>6</td>
</tr>
<tr>
<td>High</td>
<td>Some disruption to production line.</td>
<td>100% of product may have to be scrapped. Loss of primary function. Item unusable. Customer very dissatisfied.</td>
<td>7</td>
</tr>
<tr>
<td>Very High</td>
<td>Major disruption to production line.</td>
<td>Failure occurs without warning. The failure mode affects safe operation and involves noncompliance with regulations</td>
<td>8</td>
</tr>
<tr>
<td>Hazard with warning</td>
<td>May endanger machine or operator.</td>
<td>Failure occurs without warning. The failure mode affects safe operation and involves noncompliance with regulations</td>
<td>9</td>
</tr>
<tr>
<td>Hazard without warning</td>
<td>May endanger machine or operator.</td>
<td>Failure occurs without warning. The failure mode affects safe operation and involves noncompliance with regulations</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 2-2 Occurrence Ranking and suggested criteria

<table>
<thead>
<tr>
<th>Notional Probability of failure</th>
<th>Evaluated Rate</th>
<th>Failure Rate</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote: Failure is unlikely. No Failures ever associated with almost identical processes</td>
<td>1in 1,500,000</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Very Low: Only Isolated Failures associated with almost identical processes</td>
<td>1in 150,000</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Low: Isolated Failures associated with similar processes</td>
<td>1in 15,000</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Moderate: Generally associated with processes similar to previous processes Failures, but not in 'major' proportions</td>
<td>1in 2,000.</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Beyond Moderate</td>
<td>1in 400</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Moderately</td>
<td>1in 80</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>High: Generally associated with processes similar to previous processes that have often failed</td>
<td>1in 20</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Very High: Failure is almost inevitable</td>
<td>1in 8.</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Extremely High</td>
<td>1in 3</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>1in 2</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 2-3 Detection Ranking and suggested criteria

<table>
<thead>
<tr>
<th>Detection</th>
<th>The likelihood the Controls will detect a Defect</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almost Certain</td>
<td>Current likelihood the current controls will detect the Failure Mode.</td>
<td>1</td>
</tr>
<tr>
<td>Very High</td>
<td>Very High likelihood the current controls will detect the Failure Mode.</td>
<td>2</td>
</tr>
<tr>
<td>High</td>
<td>High likelihood the current controls will detect the Failure Mode.</td>
<td>3</td>
</tr>
<tr>
<td>Moderately High</td>
<td>Moderately high likelihood that the current controls will detect the Failure Mode.</td>
<td>4</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate likelihood that the current controls will detect the Failure Mode.</td>
<td>5</td>
</tr>
<tr>
<td>Low</td>
<td>Low likelihood that the current controls will detect the Failure Mode.</td>
<td>6</td>
</tr>
<tr>
<td>Very low</td>
<td>Very Low likelihood that the current controls will detect the Failure Mode</td>
<td>7</td>
</tr>
<tr>
<td>Remote</td>
<td>Remote likelihood that the current controls will detect the Failure Mode</td>
<td>8</td>
</tr>
<tr>
<td>Very Remote</td>
<td>Very Remote likelihood that the current controls will detect the Failure Mode</td>
<td>9</td>
</tr>
<tr>
<td>Almost Impossible</td>
<td>No known controls available to detect the Failure Mode.</td>
<td>10</td>
</tr>
</tbody>
</table>

The priority setting is usually based on the Failure mode Risk Priority Number (RPN):

\[ RPN = \text{Severity} \times \text{Occurrence} \times \text{Detection} \]

After each analysis, the suggestion of corrective actions for system dependability and safety is another merit of performing FMEA.

*Analysis assumption*: It is assumed that only the component undergoing analysis is in its failure mode at the moment of analysis, while others are in perfect state.

The table below shows the structure of FMEA table headings. Full and complete tables for the running example and case studies are given later in chapters 3 and 5, respectively.

This table heading is found in literature. Its elements are used in the FMEA metamodel, as explained in chapter 3 of this thesis.

Table 2-4 Structure of FMEA table

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
</table>


2.4 Related work on FMEA using software models and/or model transformation

The survey [BERN12] of existing works on software dependability analysis based on the transformation of UML software model (source model) to different types of dependability analysis models (target model) shows that there are very few works that attempt to transform UML software models to FMEA models.

This section explores some related works on FMEA making use of software models, with special attention to the semi or automatic derivation of the FMEA table by model transformation technique. For example, in [DAV09] the use of both UML/SysML models is explored, by building FMEA models from the functional analysis of the software models. The authors analyze a set of use cases, taking into account the sequence diagram of every use case, from which all system functions can be identified. But this approach had a significant limitation, namely the production of “too many lines” in the generated table, which can lead to difficulty in risk identification. Therefore, the authors proposed to create a “dysfunctional database” that describes the significant failure modes for each component. The enhanced algorithm identifies the component type that participates in a use case and fetches the corresponding failure modes from the database. Thereafter, the generated FMEA table was more precise, due to the fact that only the significant failure modes were identified in the database.

FMEA was used in [GUI03] for a Tele-echography (TER) system. TER was developed to allow an expert physician (the operator) to move or adjust by hand a scanner virtual probe in an unconstrained way and then the system safely reproduces the movement on the remote patient. The paper presents the risk management general concepts and the holistic functional analysis of the system, and applies FMECA for risk assessment. The
project used some UML elements like Use Case, Sequence diagram, Object diagram, Deployment and Class diagram for the system analysis, but there is no automated model transformation.

In [HAS05] it is proposed a severity assessment methodology by combining three different analysis techniques: Functional Failure Analysis (FFA), Failure Mode and Effect Analysis (FMEA), and Fault Tree Analysis (FTA), but the analysis was not really automated.

In [BOW01] it is shown how FMEA can be applied to a microprocessor based control system. The details of this work are used as a running example in this thesis.

In [KUM13] introduce the so-called functional modeling of the system functions. The identified system functions are used in a parameter diagram to identify the FMEA potential failure modes and failure causes. Furthermore, the parameter diagram information is inputted into a modified FMEA format that links the higher level functions, failure modes and failure causes to the lower level building blocks and associated failure modes.

In [GUI04a] the UML is used as a description language and FMEA is used as a risk analysis technique.

In [OZA04] it is analyzed how FMEA can be better performed at a higher level of software development rather than the very detailed level.
<table>
<thead>
<tr>
<th>Paper</th>
<th>Source Model</th>
<th>Target Model</th>
<th>Proposed approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>[DAV09]</td>
<td>“Improving reliability studies with SysML.”</td>
<td>SysML UML</td>
<td>FMEA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sequence Diagram and Dysfunctional Database</td>
<td>The introduction of Dysfunctional Database</td>
</tr>
<tr>
<td>[GUI03]</td>
<td>“Integration of UML in human factors analysis for safety of a medical robot for tele-echography,”</td>
<td>UML Diagrams</td>
<td>FMECA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manual generation of FMECA</td>
</tr>
<tr>
<td>[HAS05]</td>
<td>“UML Based Severity Analysis Methodology”</td>
<td>UML Diagrams</td>
<td>FMECA, FFA and FTA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Use case and Sequence diagram)</td>
<td>Not specific and target model generation not automated.</td>
</tr>
<tr>
<td>[BOW01]</td>
<td>“Software Failure Modes and Effects Analysis for a Small Embedded Control System”</td>
<td>Software Flow Chart</td>
<td>FMEA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Functional blocks breakdown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Functional Diagram)</td>
<td>Use of Parameter Diagram (P-diagram)</td>
</tr>
<tr>
<td>[GUI04a]</td>
<td>UML based risk analysis – Application to a medical robot</td>
<td>UML Use case, Sequence</td>
<td>PHA, FMEA or FTA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manual generation of the target model.</td>
</tr>
<tr>
<td>[OZA04]</td>
<td>“Failure Modes and Effects Analysis during Design of Computer Software”</td>
<td>UML Diagrams</td>
<td>SWFMEA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manual generation of FMEA</td>
</tr>
</tbody>
</table>
3 Chapter: High Level View of the Proposed Approach

This chapter presents the high-level view of the process used for deriving the FMEA model from UML + FMEA Profile model. It describes also the source and target models.

3.1 Overview of the Thesis approach

In order to generate a FMEA model automatically from a UML software model, we have developed a multi-step process shown in Figure 3.1, which includes models transformation and model editing steps.

![Figure 3-1 The multi-step process for deriving the FMEA model](image)

This process is composed of the following steps:

*Step 1. Building the source model:* With the help of a standard UML editor, construct the source UML software model and annotate it with failure mode information provided by the safety analyst as described in section 3-3. In this work we used the open-source UML editor Papyrus [PAP15] whose development is supported by PolarSys [Pola16], an
Eclipse Industry Working Group created by large industry players and tool providers to work together on the creation and support of Open Source tools for the model-driven development of embedded systems.

**Step 2. Epsilon ETL transformation:** this is the major step of the process, in which the target FMEA model is generated from the source UML model. The generated model is exported by the transformation tool to XML format. This step bridges the big semantic gap between UML and FMEA models.

**Step 3. Post-transformation processing:** At this stage some very minor editing of the generated XML file (preliminary FMEA model) is carried out in order to prepare it for the next step, as described in section 4.5.

**Step 4. Transformation to text:** This step transforms the generated FMEA model from XML to the FMEA table in text format using XSLT, as described in section 4.6.

### 3.1.1 Fmode Profile Definition

In order to transform a UML model to FMEA, we need to add failure mode information to the UML model elements, such as components, classes and messages. This requires the definition of the Fmode profile shown in Figure 3-3. The most important element of the profile is the Fmode stereotype, which extends several UML metaclasses as shown in the diagram below. The Stereotype Fmode has the following attributes: Name (of type String), Severity (of type SeverityLevel), Occurrence (of type OccurrenceLevel) Detection (of Type DetectionLevel), FailureLocalEffect (of type String) and FailureSystemLevelEffect (of type String). Three enumeration types, SeverityLevel, OccurrenceLevel and DetectionLevel are also defined, corresponding to Tables 2-1, 2-2 and 2-3.
3.2 FMEA Domain Model

As already mentioned, FMEA is a classical system safety analysis technique which is widely used in the safety critical industries like aerospace, automotive etc. [PAP04]. The FMEA domain model as shown in Figure3-4 is similar with the domain model proposed in [TAGU11]. This model consists of the following main elements: System, Component, Failure mode, Failure Cause, Failure Effects (Local Failure Effect and System Level Failure Effect), Detection Method, Occurrence and Severity. The mapping of the
elements of the FMEA domain model to UML model elements is as follows: System corresponds to the UML Model package element (the root element), Component corresponds to Part in the Composite Structure and UML Lifeline in the Sequence diagram; Failure Cause corresponds to UML Message in Sequence diagram and Information Flow in Composite Structure diagram. The remaining domain model elements, such as Failure Mode, Failure Effect and Detection Method are specialized to the FMEA domain and cannot be mapped directly to any UML model elements.

Therefore, we defined the $Fmode$ profile (see section 3.1.1), which contains the $Fmode$ stereotype and its attribute that correspond to these specialized elements. When we need to add failure mode information to a UML model, we apply the $Fmode$ profile, as described in section 3.3.
3.3 The Source Model

The source model represents a software system expressed in UML2.5 [UML14] extended with the *Fmode* profile to add failure mode information. The UML diagrams composing the model and the transformed model elements in the transformation rules are described with stereotypes applied to them. This section explains in details how the UML model elements and *Fmode* stereotype are used in the source model, explaining how the source model and its elements are required to be constructed in order to be compatible with the transformation.

The basic UML diagrams contained in a source model for the transformation are a *Composite Structure* diagram representing the system structure and one or more *Sequence* diagrams representing the system behavior, all annotated with the *Fmode* profile. Figure 3-4 and Figure 3-5 show examples of Composite Structure diagram and Sequence diagrams respectively, both diagrams together form a source model for the transformation developed in the thesis. A UML *Composite Structure* diagram represents the system structural composition based on system’s the classes’ decomposition and encapsulation that shows the internal collaboration structure of the system’s parts (i.e., instance roles linked together by connectors) [UML15]. A UML *Sequence* Diagram is a kind of system behavior diagram that focuses on the Message exchange between a number of Lifelines, it shows the interactions that model the ordered sequences of event occurrences in the system [UML15]. In this thesis, UML Sequence diagram is used to model the flow of interaction and event occurrence that compose a scenario; a model may contain one or more scenarios, each represented by a sequence diagram.
3.3.1 Running Example of a Small Embedded Control System

As a running example to be used for explaining the transformation, we have selected an FMEA case study from literature, in order to reduce the potential “author bias” that arises when using only self-constructed systems. This example is the control system of a ball-in-a-tube system, which has the basic objective of regulating the inflow of air into a tube to constantly suspend a small ball at a predetermined height called the set-point [BOW01]. The height or suspension level of the ball corresponds to the rate of the air inflow; the ball goes up when the flow is stronger, and comes down when is weaker. The system consists of a 3-foot long clear plastic tube, a lightweight ball (ping pong ball), a small electric fan, an infrared sensor circuit for detecting the balls position in the tube, a drive circuit, and an MC68000 micro controller. The block diagram is shown below.

![Figure 3-4 The Block Diagram of the close loop control system [BOW01]]
As shown above, the height of the ball is measured by the system’s infrared sensor. The white color of the ball enhances the infrared light from an emitter to properly reflect from its surface into the system’s sensor. The output voltage of the sensor is sampled by the Analog to Digital Converter (ADC) built into the microprocessor. The input voltage received is further converted into a one-byte value by the ADC, which in turn is what determines ball height. Below are the Composite Structure diagram and the Sequence diagram of the system and the generated FMEA by the transformation. Figure 3-8 below represents the ball-in-a-tube control system composite structure diagram showing the internal structure of the system and the application of the *Fmode* Stereotype.

![Composite Structure Diagram](image)

**Figure 3-5** The source model composite structure diagram for the running example
Also, Figure 3-9 represents the Sequence diagram of the control system, showing the interaction messages and the Fmode profile application.

![Sequence diagram](image)

Figure 3-6 The source Model interaction (Sequence) diagram for the running example

The structure model from Figure 3-5 contains a composite structure representing the subsystem Ball Controller, which in turn contains the following parts: Input Control Circuit, Micro-Controller, ISR and Output Control Circuit. The Ball Controller interacts with other model elements represented as class instances: Sensor, Ball and Fan. The failure mode annotations are attached to structural elements via the Fmode stereotype. For example, the sub-window at the bottom of Figure 3-5 shows the attribute values of the stereotype Fmode applied to the selected InformationFlow element called New Duty.
Cycle. All the stereotype’s attributes (Name, Severity, Detection, Occurrence, FailureLocalEffect, FailureSystemEffect) are shown in the sub-window at the bottom of the screen shot from Figure 3-6, with the values assigned by the system safety analyst. Each of the stereotype’s attributes is transformed to the corresponding target element located on the seventh line in the FMEA table shown in Table 3-1. The Failure Cause corresponds to the InformationItem conveyed by the InformationFlow, while the Property (InformationTarget) corresponds to the target model Component. Attaching failure mode annotations as stereotype to different model elements in the structure and behavior views of the system aids the system safety analyst to be able to focus on the specific context where failures may occur.

Figure 3-6 shows a sequence diagram of the running example, which represents the exchange of messages between the Lifelines. Adding failure mode annotation to the diagram helps the safety analyst to focus on the system interaction development. For instance, in Figure 3-6 the attributes of the Fmode stereotype applied to the Message “A/D Conversion Get Value_Message” are shown within the blue box at the bottom of the figure. Each of the stereotype’s attribute is transformed into a column of the corresponding target failure mode element, which is located on the sixth line of the generated FMEA table shown in Table 3-1. Its Failure Cause corresponds to the received MessageOccurrenceSpecification while the Lifeline receiving the message corresponds to the target model Component.
3.4 The target model

The FMEA Metamodel used for the transformation is shown in the Figure 3-7 below. It is a simplified representation of the FMEA domain model from Figure 3-3, where the class DetectionMethod has become the Detection attribute of FailureMode, and the two subclasses of FailureEffect have become the FailureLocalEffect and SystemFailureLevelEffect attributes of FailureMode. Only the class FailureCause, which has a one-to-many association with FailureMode is represented as a separate class.

![Diagram of modified FMEA Metamodel](image)
@namespace(uri=\"FMEA\", prefix=\"\")

package System;

class System {
    attr String name;
    val Component[*] component;
}

class Component {
    attr String name;
    val FailureMode[*]#component failuremode;
}

class FailureMode {
    attr String name;
    attr String FailureLocalEffect;
    attr String SystemFailureLevelEffect;
    attr String severity;
    attr String occurrence;
    attr String detection;
    attr int RPN;
    ref Component[0..1]#failuremode component;
    val FailureCause[*]#failuremode failurecause;
}

class FailureCause {
    attr String name;
    ref FailureMode[1]#failurecause failuremode;
}
Figure 3-8 is the description in the language Emphatic of the FMEA metamodel in class diagram form, as required by the Epsilon transformation. It shows the metamodel main package, the classes, their attributes and types and also the relationships and association role names. Figure 3-9 below shows the mapping of the FMEA metamodel represented as a class diagram to its corresponding Emphatic description.

The outcome of the Model-to-Model transformation from UML to FMEA is shown in the screen shot in Figure 3-13 below. The UML model can be exported to XML format, an intermediate format [LI14] that shows the FMEA objects, the relationships and the attributes (as shown in the Appendix).
The Table below shows the output FMEA table generated from the auto-generated FMEA XML file (shown in Appendix A1) generated from the UML model. The component column shows that a component can have more than one Failure mode, each one with its own set of elements: Local Effect, System Level Effect, Severity, Occurrence, Detection, RPN, and Failure Cause.
<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>Failure to get or convert position</td>
<td>Fan speed does not change</td>
<td>Inadequate or no control</td>
<td>Hazard without Warning</td>
<td>Moderate</td>
<td>Almost Certain</td>
<td>40</td>
<td>Light intensity_MessageRecv</td>
</tr>
<tr>
<td>Input Control Circuit</td>
<td>Incorrect Input value</td>
<td>Can not get or convert</td>
<td>Fan speed does not change</td>
<td>Ball falls to the bottom of the tube</td>
<td>Very High</td>
<td>Very Low</td>
<td>Low</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Failure to initialize input pin register</td>
<td>Fan does not run</td>
<td>Ball falls to the bottom of the tube</td>
<td>Hazard without Warning</td>
<td>Beyond moderate</td>
<td>Remote</td>
<td>400</td>
<td>Convert Position_MessageRecv</td>
</tr>
<tr>
<td>Micro-Controller</td>
<td>Incorrect value in register</td>
<td>Fan speed is incorrect</td>
<td>Inadequate or no control</td>
<td>Ball falls to the bottom of the tube</td>
<td>High</td>
<td>Beyond moderate</td>
<td>35</td>
<td>ADC value</td>
</tr>
<tr>
<td></td>
<td>Loss of output signal to drive the circuit</td>
<td>Fan does not run or system does not respond</td>
<td>Ball falls to the bottom of the tube</td>
<td>High</td>
<td>Very High</td>
<td>Moderately High</td>
<td>224</td>
<td>Initialize Input Pin_Register_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Too much delay in getting value</td>
<td>Fan speed is incorrect</td>
<td>Inadequate or no control</td>
<td>Ball falls to the bottom of the tube</td>
<td>Very Low</td>
<td>Extremely High</td>
<td>324</td>
<td>A/D Conversion Get value_MessageRecv</td>
</tr>
<tr>
<td>Output too high</td>
<td>Fan runs too fast</td>
<td>Ball is shot to the top of the tube and possibly damages the sensor</td>
<td>Hazard With Warning</td>
<td>Moderately High</td>
<td>Very Low</td>
<td>378</td>
<td>Compute Duty Cycle_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Output Control Circuit</td>
<td>Failure to initialize IRS</td>
<td>Can not read Input</td>
<td>Ball falls to the bottom of the tube</td>
<td>High</td>
<td>Low</td>
<td>Very Low</td>
<td>147</td>
<td>PWM Period_MessageRecv</td>
</tr>
<tr>
<td>Output too high</td>
<td>Fan runs too fast</td>
<td>The ball is shot to the top of the tube and possibly damages the sensor</td>
<td>Hazard without Warning</td>
<td>Moderate</td>
<td>Moderately High</td>
<td>160</td>
<td>New duty cycle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incorrect value in register</td>
<td>Incorrect output</td>
<td>Inadequate or no control</td>
<td>Low</td>
<td>Moderate</td>
<td>Very Remote</td>
<td>180</td>
<td>OutPut signal_Gateภาว_MessageRecv</td>
</tr>
<tr>
<td>D4 (input duty cycle) stuck high</td>
<td>Fan runs too fast</td>
<td>Ball is shot to the top of the tube and possibly damages the sensor</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
<td>21</td>
<td>IRS trigger</td>
<td></td>
</tr>
<tr>
<td>D4 (Input duty cycle to IRS) stuck low</td>
<td>Fan does not run or runs too slow</td>
<td>Ball falls to bottom of tube</td>
<td>Hazard without Warning</td>
<td>Moderately High</td>
<td>Remote</td>
<td>480</td>
<td>Initialize_ISR_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>ISR</td>
<td>Fan Pin PBO (output parm.) Output stuck</td>
<td>Fan run incorrectly (fast if stuck high and too slow or dose not run at all if stuck low)</td>
<td>Ball shot to the top of the tube or ball falls to the bottom of the tube (if stuck low)</td>
<td>Low</td>
<td>Moderate</td>
<td>Remote</td>
<td>160</td>
<td>Regulate Speed_MessageRecv</td>
</tr>
</tbody>
</table>
4 Chapter: Design and Implementation of the Transformation

This chapter presents the design and implementation of the transformation. The design starts by deciding the mapping between the source and target models. The implementation is the description of the ETL code and the effect of each rule and operation. Figure 4-1 below shows the mapping of the source model elements with the target model.

Figure 4-1 Mapping between the source and target model
4.1 Mapping between the Source and Target Elements

At the beginning of the design of the transformation, we need to decide what elements of the target model are obtained from what elements of the source model. Table 4-1 shows this mapping.

<table>
<thead>
<tr>
<th>UML Model Element</th>
<th>FMEA Stereotype, attribute</th>
<th>FMEA Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>None</td>
<td>FMEA Model</td>
</tr>
<tr>
<td>Property (Name)</td>
<td>Fmode</td>
<td>Component</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(Name)</td>
<td>Failure Mode</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(FailureSystemEffect)</td>
<td>SystemFailureLevelEffect</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(FailureLocalEffect)</td>
<td>FailureLocalEffect</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(Severity)</td>
<td>Severity</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(Occurrence)</td>
<td>Occurrence</td>
</tr>
<tr>
<td>InformationFlow</td>
<td>Fmode(Detection)</td>
<td>Detection</td>
</tr>
<tr>
<td>InformationItem</td>
<td>None</td>
<td>FailureCause</td>
</tr>
<tr>
<td>Lifeline</td>
<td>None</td>
<td>Component</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(Name)</td>
<td>FailureMode</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(FailureSystemEffect)</td>
<td>SystemFailureLevelEffect</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(FailureLocalEffect)</td>
<td>FailureLocalLevelEffect</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(Severity)</td>
<td>Severity</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(Occurrence)</td>
<td>Occurrence</td>
</tr>
<tr>
<td>Message</td>
<td>Fmode(Detection)</td>
<td>Detection</td>
</tr>
<tr>
<td>MessageOccurrence</td>
<td>None</td>
<td>FailureCause</td>
</tr>
<tr>
<td>Specification</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 Rules and Operations

This thesis transformation has been designed in an ETL module, which consists of all the transformation rules and operations used to carry out all source-to-target model mappings given in Table 4-1. The rule table (Table 4-2) below shows the FMEA elements that are created for the source elements discovered in the input model. Each operation described in the Table 4-3 below represents a function called by the rules or by other operations during the transformation. An operation verifies a set of conditions and returns the corresponding results.

The Epsilon Transformation Language (ETL) is one of the Epsilon task specific language [KOL15] that can be used in the transformation of an arbitrary number of input models into an arbitrary number of output models of different modeling languages and technologies at a high level of abstraction. ETL is a hybrid kind of transformation language, as it provides both a declarative rule-based execution scheme, as well as imperative features for handling complex transformation scenarios [KOL15]. ETL rule may be either “Matched” or “Lazy” rules, where a Matched rule corresponds to the declarative style, while a Lazy rules corresponds to the imperative style. From the code fragments that show the rules syntax the logic for connecting each generated target element with another is defined within each rule. The containment association relationships are used to link the target elements together. The first rule Model2System is a Matched rule, which transform the root element (UML Model) of the source model to the target’s (FMEA Model) root element (System). System in turns has a containment relationship with the target’s element Component. The target element Component has a containment relationship with the target element Failure Mode, which in turn has a
containment relationship with the target element *Failure Cause*. The generated FMEA *Failure Cause* has to be added as a *child* to the target element *Failure Mode*. The matched rule *Informationflow2FailureMode* and *Message2FailureMode* invoke the lazy rules *InformationItem2FailureCause* and *MessageOccurrenceSpecification2FailureCause* to generate a target *Failure Cause* for each target’s *Failure Mode* element found in the input model, and then adds the newly created target elements to the corresponding container *FMEA model element*.

Table 4-2 Table of Rules in the UML to FMEA Transformation

<table>
<thead>
<tr>
<th>Rule Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model2System</td>
<td>Transform UML Model Element (source root) to FMEA System Element (target root)</td>
</tr>
<tr>
<td>Lifeline2Component</td>
<td>Transform UML Lifeline to FMEA Component Element</td>
</tr>
<tr>
<td>Property2Component</td>
<td>Transform UML Composite Structure Property (a part of the composite structure) to FMEA Component Element</td>
</tr>
<tr>
<td>Message2FailureMode</td>
<td>Transform UML Sequence Diagram message to FMEA Failure Mode Element</td>
</tr>
<tr>
<td>InformationFlow2FailureMode</td>
<td>Transform UML Composite Structure Diagram Information Flow to FMEA Failure Mode Element</td>
</tr>
<tr>
<td>MessageOccurrenceSpecification2FailureCause</td>
<td>Transform UML Sequence Diagram Message Occurrence Specification to FMEA Failure Cause Element</td>
</tr>
<tr>
<td>InformationItem2FailureCause</td>
<td>Transform UML Composite Structure Diagram Information Item to FMEA Failure Cause Element</td>
</tr>
</tbody>
</table>
Table 4-3: Table of Operations in the UML to FMEA transformation

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MessageEndisReceive ()</td>
<td>For the given UML Message defined in Sequence diagram, returns true and the message if the message occurrence specification event is a receive event</td>
</tr>
<tr>
<td>MessageEndisSend ()</td>
<td>For the given UML Message defined in Sequence diagram, returns true and the message if the message occurrence specification event is a send event</td>
</tr>
<tr>
<td>MessagehasStereotype ()</td>
<td>For the given UML Message defined in Sequence diagram, returns the String value of all the properties of its FMode stereotype</td>
</tr>
<tr>
<td>MessageOccurrenceSpecificationisThisReceiveMessage ()</td>
<td>For the given UML Message Occurrence Specification defined in Sequence diagram, returns true if the Message Occurrence specification event is a ReceivedMessage.</td>
</tr>
<tr>
<td>MessageOccurrenceSpecificationisThisSendMessage ()</td>
<td>For the given UML Message Occurrence Specification defined in Sequence diagram, returns true if the Message Occurrence specification event is a SendMessage.</td>
</tr>
<tr>
<td>InformationFlowhasStereotype()</td>
<td>For the given UML Information Flow defined in Composite Structure diagram, returns the String value of all the properties of its FMode stereotype</td>
</tr>
<tr>
<td>LifelinehasStereotype ()</td>
<td>For the given UML Lifeline defined in Sequence diagram, returns true if the Lifeline possessed the FMode stereotype</td>
</tr>
<tr>
<td>PropertyhasStereotype ()</td>
<td>For the given UML Class property defined in Composite Structure diagram, returns true if the Property possessed the FMode stereotype</td>
</tr>
<tr>
<td>operation ReturnDetectionValue()</td>
<td>Returns the equivalent integer value of the target Detection string value</td>
</tr>
<tr>
<td>operation ReturnSeverityValue()</td>
<td>Returns the equivalent integer value of the target Severity string value</td>
</tr>
<tr>
<td>operation ReturnOccurrenceValue()</td>
<td>Returns the equivalent integer value of the target Occurrence string value</td>
</tr>
</tbody>
</table>
4.3 Detailed description of Rules

4.3.1 Rule Model2System

The System element is the top element of the target FMEA model. The System element serves as the root container of the target model. System corresponds to the source root container, the UML Model element. Just as shown in Code Fragment 4-1 below, the UML Model element, which is the root container of the source model, indicated in the rule line “transform”, is transformed to the top FMEA model element System.

The rule contains a target element preceded with the keyword “to”, which is labeled with the variable Fmea. This is a variable that represents the generated target node of type System. The assignment statement involving the target node Fmea:

\[ \text{Fmea.name} = \text{"FMEA of" ~+~ m.name} \]

shows that the Fmea.name attribute is initialized with a string composed of “FMEA of” to which the name of the source Model appended. The operation isDefined () is invoked on the variable \( i \) that represents the UML Lifeline element of the source model, which returns a Boolean result. For each true returned, the call to \( i.equivalent() \) returns the FMEA model element Component transformed from \( i \), which is then added to the collection Fmea.component. The operation equivalent() is a built-in ETL operation that resolves the target elements that have been transformed from its corresponding source elements by other rules in the transformation [KOL15]. Figure 4-2 illustrates the transformation of the source model element name to the corresponding target model element name.
rule model2system
    transform m: UML!Model
to Fmea: FMEA!System {
    Fmea.name = "FMEA of "+m.name;
    var Lifeline: Any = UML!Lifeline.all;
    for (i in Lifeline) {
        if (i.isDefined()){
            Fmea.component.add( i.equivalent());
        }
    }
}
4.3.2 Rule Lifeline2Component

Each *Lifeline* element from the UML Sequence diagram of the source model is mapped to a *Component* element of the target FMEA model as depicted Code Fragment 5-4 and shown in Figure 4-3 and Figure 4-4.

Figure 4-3 Transformation rule example: Rule Lifeline2Component
In this transformation, the name of a target Component will be initialized to the name of its corresponding source UML Lifeline or UML Property (i.e. Lifeline.represents). The ETL built-in operation isDefined() is invoked on the variable l.represents (see Figure 4-3)

```
rule lifeline2component
    transform l: UML!Lifeline
    to C: FMEA!Component
    {
        C.name = l.name;
        var o:Collection;
        if (l.represents.isDefined()){
            var Inf:Any = InformationFlow;
            var In : String;
            for (i in Inf) {
                if (i.target.selectOne(a|a.name=l.represents.name).isDefined()){
                    C.failuremode.add( i.equivalent());
                }
            }
        }
        if (l.name.isDefined()){
            var Inf:Any = Message;
            var In : String;
            for (i in Inf) {
                if (i.receiveEvent.covered.selectOne
                    (a|a.name=l.name).isDefined()){
                    C.failuremode.add( i.equivalent());
                }
            }
        }
    }
```

Code Fragment 4-2 Rule Lifeline2Component
and l.name which refer to UML Property and UML Lifeline.name, respectively, to return a Boolean result. For each true returned, the call .equivalent() returns the FMEA model element Failure Mode transformed from both UML InformationFlow and UML Message, which is then added to the collection FC.failuremode.

Figure 4-4 Transformation rule example: Lifeline2Component with reference to the represented Composite structure Property
4.3.3 Rule InformationFlow2FailureMode

This rule transforms the source model element UML InformationFlow from the Composite Structure diagram to the target component Failuremode, as it can be seen in Code Fragment 4-3 and Figure 4-5. The “guard” section of the rule checks for the UML InformationFlow stereotyped with Fmode. If there are UML InformationFlow in the source model that are not stereotyped with the Fmode stereotype, those elements will not be considered in the transformation rule. Every transformation rules that include a “guard” section will be applicable only to the elements that satisfy the stated guard’s condition. Furthermore, operation getAllAttributes() retrieves all the attributes of the Fmode stereotypes applied to InformationFlow, which includes name, Occurrence, Severity, Detection, FailureLocalEffect and FailureSystemEffect and transforms them to the corresponding target model element FailureMode attributes: name, Occurrence, Severity, Detection, FailureLocalEffect and FailureSystemLevelEffect respectively, as shown in the Code Fragment 4-3 and Figure 4-5, which illustrates the source elements to target elements transformation. The RPN column corresponds to the product of the integer value of Severity, Occurrence and Detection of each FailureMode element. The conversion of these three attributes from string value to integer value is performed with the operations ReturnOccurrenceValue(), ReturnServerityValue() and ReturnDetectionValue(), respectively.
Figure 4-5 Transformation rule example: InformationFlow2FailureMode (Name, Effects, Severity, Occurrence and Detection)
rule informationflow2FailureMode
transform I : UML! InformationFlow
to FM : FMEA! FailureMode {
    guard I.isDefined() = I.hasStereotype("FMode")
    var hasSte: Any = I.hasStereotype("FMode");
    var stereotype: Any = I.getAppliedStereotypes();
    if (stereotype.isDefined()) {
        for (s in stereotype) {
            if (s.name = "FMode") {
                if (s.getAllAttributeS().selectOne(a|a.name = "FailureLocalEffect").isDefined()) {
                    FM.FailureLocalEffect = I.getValue(s, "FailureLocalEffect").asString();
                }
                if (s.getAllAttributeS().selectOne(a|a.name = "FailureSystemEffect").isDefined()) {
                    FM.SystemFailureLevelEffect = I.getValue(s, "FailureSystemEffect").asString();
                }
                if (s.getAllAttributeS().selectOne(a|a.name = "Name").isDefined()) {
                    FM.name = I.getValue(s, "Name").asString();
                }
                if (s.getAllAttributeS().selectOne(a|a.name = "Occurrence").isDefined()) {
                    FM.occurrence = I.getValue(s, "Occurrence").asString();
                }
                if (s.getAllAttributeS().selectOne(a|a.name = "Severity").isDefined()) {
                    FM.severity = I.getValue(s, "Severity").asString();
                }
                if (s.getAllAttributeS().selectOne(a|a.name = "Detection").isDefined()) {
                    FM.detection = I.getValue(s, "Detection").asString();
                }
                var Det: Integer = 1;
                var Sev: Integer = 1;
                var Occ: Integer = 1;
                Sev = ReturnSeverityValue(FM.severity);
                Det = ReturnDetectionValue(FM.detection);
                Occ = ReturnOccurrenceValue(FM.occurrence);
                FM.RPN = Det * Sev * Occ;
            }
        }
    }
    var Item : Any = I.conveyed;
    for (i in Item) {
        FM.failurecause.add(i.equivalent());
    }
}
4.3.4 Rule Message2FailureMode

This rule is structured in a similar manner to the above rule InformationFlow2FailureMode, as shown in the code fragment 4.4 and illustrated in Figure 4-6. It transforms the source model element UML Message from a sequence diagram to the target element FailureMode. Also, the “guard” section of the rule checks whether the source element Message is stereotyped with Fmode. If there are messages in the source model that are not stereotyped with Fmode, such messages will be ignored by the transformation rule.

If the Stereotype “Fmode” is applied to the UML Message and its attributes are defined, the operation getAllAttributes() returns the value of the following attributes: name, Occurrence, Severity, Detection, FailureLocalEffect and FailureSystemEffect. For every source model element Message, these attributes are transformed to the corresponding target model element FailureMode attributes: name, Occurrence, Severity, Detection, FailureLocalEffect and FailureSystemLevelEffect, respectively. Here as well, the RPN corresponds to the product of the integer value of Severity, Occurrence and Detection of the corresponding target element FailureMode. The integer values of Severity, Occurrence, and Detection are obtained by calling the operations ReturnServerityValue(), ReturnOccurrencevalue() and ReturnDetectionValue(). These operations when invoked return the integer value corresponding to the string value of the respective element.
**Code Fragment 4-4 Rule Message2FailureMode**

```java
rule Message2FailureMode
  transform op : UML!Message
to FM: FMEA!FailureMode{
  guard: op.hasStereotype("FMode")
  var hasSte: Any = op.hasStereotype("FMode");
  var stereotype: Any = op.getAppliedStereotypes();
  if (stereotype.isDefined()){
    for (s in stereotype) {
      if (s.name = "FMode") {
        if (s.getAllAttributeS().selectOne(a|a.name = "Occurrence").isDefined()) {
          FM.occurrence = op.getValue(s,"Occurrence").asString();
        }
        if (s.getAllAttributeS().selectOne(a|a.name = "FailureLocalEffect").isDefined()) {
          FM.FailureLocalEffect = op.getValue(s,"FailureLocalEffect").asString();
        }
        if (s.getAllAttributeS().selectOne(a|a.name = "FailureSystemEffect").isDefined()) {
          FM.SystemFailureLevelEffect = op.getValue(s,"FailureSystemEffect").asString();
        }
        if (s.getAllAttributeS().selectOne(a|a.name = "Name").isDefined()) {
          FM.name = op.getValue(s,"Name").asString();
        }
        if (s.getAllAttributeS().selectOne(a|a.name = "Severity").isDefined()) {
          FM.severity = op.getValue(s,"Severity").asString();
        }
        if (s.getAllAttributeS().selectOne(a|a.name = "Detection").isDefined()) {
          FM.detection = op.getValue(s,"Detection").asString();
        }
      }
    }
    var Det: Integer;
    var Sev: Integer;
    var Occ: Integer;
    Sev = ReturnSeverityValue(FM.severity);
    Det = ReturnDetectionValue(FM.detection);
    Occ = ReturnOccurrenceValue(FM.occurrence);
    FM.RPN = Det*Sev*Occ;
  }
}

var Item : Any = op.receiveEvent;
for (i in Item) {
  FM.failurecause.add(i.equivalent());
}
```
4.3.5 Rule **InformationItem2FailureCause**

This rule transforms the source model element *InformationItem* to the corresponding target model element *FailureCause*. The assignment statement *FC.name = In.name* shows how the “*FC.name*” attribute is initialized with the *name* of the source *InformationItem* element, as shown in Code Fragment 4.5 and Figure 4-7.

Figure 4-6 Transformation rule example: Message2FailureMode (Name, Effects, Severity, Occurrence and Detection)
@lazy
rule informationItem2Failurecause
  transform In :UML!InformationItem
to FC : FMEA!FailureCause {
  FC.name=In.name;
}

Code Fragment 4-5 Rule InformationItem2Failurecause

Figure 4-7 Transformation rule example: InformationItem2Failurecause
4.3.6   Rule MessageOccurrenceSpecification2FailureCause

This rule transforms the source model element *MessageOccurrenceSpecification* to the corresponding target model element *Failurecause*. In this rule the “guard” statement section of the rule checks the source element *MessageOccurrenceSpecification* invoking the operation *M.isThisReceiveMessage()*. If there are any *MessageOccurrence Specification* elements for which the guard condition is false, they will be ignored by the transformation rule.

The assignment statement *FC.name = M.name* shows that the *FC.name* attribute is initialized with the name of the source element *MessageOccurrenceSpecification*, as shown in Code Fragment 4-6 and Figure 4-8.

```
@lazy
def rule MessageOccurrenceSpecification2FailureCause
    transform M:
    UML!MessageOccurrenceSpecification
to FC: FMEA!FailureCause {
    guard: M.isThisReceiveMessage()
    FC.name=M.name;
}
```

*Code Fragment 4-6 Rule MessageOccurrenceSpecification2FailureCause*
4.4 Detailed descriptions of Operations

4.4.1 Operation hasStereotype()

This operation is called in the context of a Message of the source model and returns a Boolean type value. As we can see in the Code Fragment 4.7, the ETL built-in operation getAppliedStereotypes() is invoked on the variable self that refers to the context of this operation. Operation getAppliedStereotypes() returns a collection containing all the
stereotypes that have been applied to the respective Message. For each Stereotype instance in this collection, if the stereotype’s attribute name matches the String parameter passed as an argument to this operation, the operation will return true.

```java
operation UML!Message hasStereotype(name: String): Boolean {
    var c: Collection;
    c = self.getAppliedStereotypes();
    for (s:Stereotype in c) {
        s.println();
        if (s.name = name) {
            return true;
        }
    }
    return false;
}
```

Code Fragment 4-7 Operation Message hasStereotype()

4.4.2 Operation MessageOccurrenceSpecification is ThisReceiveMessage()

This operation is called in the context of the source element MessageOccurrenceSpecification as mentioned above to check first whether the context element is a message. If it is a received message, then the operation returns true, otherwise it returns false.

```java
operation MessageOccurrenceSpecification is ThisReceiveMessage() : Boolean {

    if (self.message.isDefined())
        if (self.isSend())
            return false;
        else if (self.isReceive())
            return true;
}
```

Code Fragment 4-8 Operation MessageOccurrenceSpecification is ThisReceiveMessage()
4.4.3 Operation MessageEndisSend()

This operation is invoked to check whether a `MessageEnd` corresponds to a send event, in which case the operation returns `true`, otherwise it returns `false`.

```java
operation MessageEndisSend() : Boolean {
    return self.message.sendEvent.asSet().includes(self);
}
```

4.4.4 Operation MessageEndisReceive()

This operation is called in the context of the source element `Message` to check if `MessageEnd` is a received message, in which case the operation returns `true`, otherwise it returns `false`.

```java
operation MessageEnd isReceive() : Boolean {
    return self.message.receiveEvent.asSet().includes(self);
}
```

4.4.5 Operation InformationFlowhasStereotype()

Here is another kind of `hasStereotype` operation named `InformationFlowhasStereotype`, which is called in the context of an `InformationFlow` element from the source model. The `getAppliedStereotypes()` returns a collection containing all the stereotypes that have been applied to the respective `InformationFlow` element. For every Stereotype instance in this
collection it is checked whether the attribute name matches the \textit{String} parameter passed as an argument. If the condition is true for one stereotype, the operation will return \textit{true}.

\begin{verbatim}
operation UML!InformationFlow\hasStereotype(name:\text{String}):Boolean{
    var c: Collection;
    c=self.getAppliedStereotypes();
    for (s:Stereotype in c){
        if(s.name=name){
            return true;
        }
    }
    return false;
}
\end{verbatim}

\textbf{Code Fragment 4-11 Operation InformationFlow HasStereotype()}

\subsection*{4.4.6 Operation Property\hasStereotype()}

This is similar to operation \textit{Message\hasStereotype()} described above, only that it is called in the context of a UML \textit{Property} of the source model. The \textit{getAppliedStereotypes()} returns a collection containing all the stereotypes that have been applied to the respective \textit{Property}. For at least one Stereotype instance in this collection, if the stereotype’s attribute name matches the String parameter passed as an argument to this operation, the operation will return \textit{true}.

\begin{verbatim}
operation Property\hasStereotype(name:\text{String}):Boolean{
    var c: Collection;
    c=self.getAppliedStereotypes();
    for (s:Stereotype in c){
        if(s.name=name){
            return true;
        }
    }
    return false;
}
\end{verbatim}

\textbf{Code Fragment 4-12 Operation UML!Propert hasStereotype()}

4.4.7 Operation ReturnOccurrenceValue()

This operation is called in the context of a target element \textit{Occurrence} to check if the \textit{Occurrence} String value is defined. If true, it returns the corresponding integer value of that string value, as shown in Code Fragment 4-13 conditional statements.

\begin{verbatim}
operation ReturnOccurrenceValue(FMoccurrence:String):Integer {
  if (FMoccurrence = "Remote") { return 1;
  } else if (FMoccurrence = "VeryLow") {
    return 2;
  } else if (FMoccurrence = "Low") {
    return 3;
  } else if (FMoccurrence = "Moderate") {
    return 4;
  } else if (FMoccurrence = "BeyondModerate") {
    return 5;
  } else if (FMoccurrence = "ModeratelyHigh") {
    return 6;
  } else if (FMoccurrence = "High") {
    return 7;
  } else if (FMoccurrence = "VeryHigh") {
    return 8;
  } else if (FMoccurrence = "ExtreemlyHigh") {
    return 9;
  } else if (FMoccurrence = "AlmostCertain") { return 10;
  }
}
\end{verbatim}

Code Fragment 4-13 operation ReturnOccurrenceValue()

4.4.8 Operation ReturnSeverityValue()

This is another operation similar to the aboved operation. This operation is called in the context of a target element \textit{Severity} to check if its string value is defined. If true, then it returns the corresponding integer value of that string as in the Code Fragment 4-14 conditional statements.
operation ReturnSeverityValue(FMseverity: String): Integer {
    if (FMseverity == "None") { return 1;
    } else if (FMseverity == "VeryMinor") {
        return 2;
        } else if (FMseverity == "Minor") {
            return 3;
        } else if (FMseverity == "VeryLow") {
            return 4;
        } else if (FMseverity == "Low") {
            return 5;
        } else if (FMseverity == "Moderate") {
            return 6;
        } else if (FMseverity == "High") {
            return 7;
        } else if (FMseverity == "VeryHigh") {
            return 8;
        } else if (FMseverity == "HazardWithWarning") {
            return 9;
        } else if (FMseverity == "HazardWithoutWarning") { return 10;
    }
}

Code Fragment 4-14 operation ReturnSeverityValue()

operation ReturnDetectionValue(FMdetection: String): Integer {
    if (FMdetection == "AlmostCertain") { return 1;
    } else if (FMdetection == "VeryHigh") {
        return 2;
    } else if (FMdetection == "High") {
        return 3;
    } else if (FMdetection == "ModeratelyHigh") {
        return 4;
    } else if (FMdetection == "Moderate") {
        return 5;
    } else if (FMdetection == "Low") {
        return 6;
    } else if (FMdetection == "VeryLow") {
        return 7;
    } else if (FMdetection == "Remote") {
        return 8;
    } else if (FMdetection == "VeryRemote") {
        return 9;
    } else if (FMdetection == "AlmostImpossible") { return 10;
    }
}

Code Fragment 4-15 operation ReturnDetectionValue()
4.4.9 Operation ReturnDetectionValue()

This operation is called in the context of the target element Detection to check if the Detection string value is defined. If true, it returns the corresponding integer value of that String value, as shown in the Code Fragment 4-15.

4.5 Post-transformation processing

The result of the ETL transformation is a preliminary FMEA model in XML format, meant to be an input to an XSLT transformation that will transform it to the FMEA table. But there is a need to manually edit the auto-generated XML file in order to delete the version and path “xmi:version="2.0" xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA"” generated with the FMEA XML file, so that the XML file can be processed by XSLT.

4.6 Generating the FMEA Table (XSLT transformation)

Producing the FMEA table is the final phase of the FMEA transformation. We decided to use the Extensible Stylesheet Language Transformations (XSLT), which is a transformation language for translating XML documents/files to another document format or another form of XML format.

XSLT can be referred to as a “turing-complete” language, that is, XSLT can specify any computation that can be performed by a computer [KEP04]. XSLT was used in this thesis to transform the XML file of the generated FMEA model to text format (FMEA table), where the input document is the FMEA XML document. In [BOS11] the author showed how XSLT transformations could be mapped to any XML Schemas to generated ontologies automatically, without subsequent manual adaptations. The Code Fragment 4-
16 below shows the XSLT transformation for the generated FMEA XML document to
FMEA table, specifying the columns and the headings of the table.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<xsl:stylesheet version="1.0"
xmlns:xsl="http://www.w3.org/1999/XSL/Transform">
<xsl:template match="/">
<html>
<body>
<h1 style="text-align:center">The <xsl:value-of select="System/@name"/></h1>
<table border="1">
<tr bgcolor="#9acd32">
<th>Component</th>  <th> Failuremode </th> <th>Local Effect</th> <th>System Effect</th>
<th>Severity</th> <th>Occurrence</th> <th>Detection</th> <th>RPN Value</th>
<th>Failure Cause</th> </tr>
<xsl:for-each select="System/component">
<tr>
<td><xsl:value-of select="@name"/></td>
<td>
<xsl:for-each select="failuremode">
<xsl:value-of select="@name"/><br/><br/><br/><br/>
</xsl:for-each></td>
<td>
<xsl:for-each select="failuremode">
<xsl:value-of select="FailureLocalEffect"/><br/><br/><br/><br/><br/>
</xsl:for-each></td>
<td>
<xsl:for-each select="failuremode">
<xsl:value-of select="SystemFailureLevelEffect"/><br/><br/><br/><br/><br/>
</xsl:for-each></td>
<td><xsl:for-each select="failuremode">
<xsl:value-of select="severity"/><br/><br/><br/><br/><br/>
</xsl:for-each></td>
<td><xsl:for-each select="failuremode">
<xsl:value-of select="occurrence"/><br/><br/><br/><br/><br/>
</xsl:for-each></td>
<td><xsl:for-each select="failuremode">
<xsl:value-of select="detection"/><br/><br/><br/><br/><br/>
</xsl:for-each></td>
<td><xsl:for-each select="failuremode/failurecause">
<xsl:value-of select="@name"/><br/><br/><br/><br/>
</xsl:for-each></td>
</tr>
</xsl:for-each>
</table>
</body>
</html>
</xsl:template>
</xsl:stylesheet>
```

**Code Fragment 4-16 FMEA Text-to-Text Transformation code (XSLT)**
5 Chapter: Verification and Validation

This section of the thesis presents different test cases used for the verification and validation of the transformation process and developed rules. Also, two case studies from [DAV10] and [GUI03] were used in order to mitigate the possible bias that could arise when using only self-built products for verification and validation.

5.1 Test Cases

In accordance with the IEEE standard IEEE-STD-610, software verification can be defined as the process of evaluating software to determine if the products of a given development phase satisfy the conditions imposed at the start of that phase, while software validation is referred to as the process of evaluating software during or at the end of the development process to determine whether it satisfies the specified requirements. The transformation processes and rules developed in this thesis have been verified by executing different level of tests using different test cases. A number of important transformation features were identified and test cases were used to verify the effectiveness (satisfaction the imposed conditions) of transformation, to check whether it produced the expected output.

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Tested Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case 1</td>
<td>Simple message and Execution Occurrence</td>
</tr>
<tr>
<td>Test case 2</td>
<td>Combined Fragment</td>
</tr>
<tr>
<td>Test case 3</td>
<td>Nested Combined Fragment</td>
</tr>
<tr>
<td>Test case 4</td>
<td>More Than One Interaction Diagram</td>
</tr>
<tr>
<td>Test case 5</td>
<td>Composite Structure and an Interaction diagram</td>
</tr>
<tr>
<td>Test case 6</td>
<td>Composite Structure and 2 Interaction Diagram</td>
</tr>
<tr>
<td>Case study 1</td>
<td>The Level Control System (LCS) [DAV10]</td>
</tr>
<tr>
<td>Case study 2</td>
<td>Robotic Tele-Echography (TER) Project [GUI003]</td>
</tr>
</tbody>
</table>
5.1.1 Test case 1

For this test case, the motive is to start the testing with the simplest level: simple messages and execution occurrence transformation to verify if all basic elements are correctly transformed. Figure 5-1 shows the sequence diagram of test case1 model, which contains two messages and two execution occurrences, and two lifelines. The FMEA model generated from the above UML model is shown in Figure 5-2.
### Table 5-2 The FMEA table for Test Case 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component1</td>
<td>Component1 Failure mode</td>
<td>Affect component 2</td>
<td>shutdown the system</td>
<td>Low</td>
<td>Beyond Moderate</td>
<td>High</td>
<td>75</td>
<td>Com from Comp2to1_MessageRecv</td>
</tr>
<tr>
<td>Component2</td>
<td>Component2 Failure mode</td>
<td>Affects Component 1</td>
<td>No effect on the system</td>
<td>Very Minor</td>
<td>Very Low</td>
<td>Almost Certain</td>
<td>4</td>
<td>Com from Comp1to2_MessageRecv</td>
</tr>
</tbody>
</table>

#### 5.1.2 Test Case 2

Test Case 2 is another simple example, but bigger than Test Case 1. It consists of just a sequence diagram with a combined fragment to test the capability of the transformation process to handle such a sequence diagram. Figure 5-3 below shows the sequence diagram and Figure 5-4 the structure diagram for test case 2.

![Test Case 2 Sequence diagram](image)

**Figure 5-3 Test Case 2 Sequence diagram**
Figure 5-4 Test Case 2 Composite Structure Diagram

Table 5-3 The FMEA table for Test Case2

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component 1</td>
<td>Failure mode2</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message0Recv</td>
</tr>
<tr>
<td></td>
<td>Failure mode4</td>
<td>Low Effect on Component2</td>
<td>Low Effect</td>
<td>Very Minor</td>
<td>Very Low</td>
<td>Almost Certain</td>
<td>4</td>
<td>Message2Recv</td>
</tr>
<tr>
<td>Component 2</td>
<td>Failure mode1</td>
<td>Stop Component1</td>
<td>Shutdown the system</td>
<td>High</td>
<td>Moderate</td>
<td>Almost Certain</td>
<td>28</td>
<td>MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Failure mode3</td>
<td>Affects Component1</td>
<td>Affects the system</td>
<td>Moderate</td>
<td>Remote</td>
<td>Very High</td>
<td>12</td>
<td>Message1Recv</td>
</tr>
</tbody>
</table>
5.1.3 Test Case 3

This is a more complex test case verifying the transformation process ability to transform a nested combined fragment. Figure 5-5 shows the sequence diagram of a nested combined fragment (Test Case 3).

Figure 5-5 Test Case 3 Sequence diagram

Figure 5-6 Test Case 3 Composite Structure Diagram
### Table 5-4 The FMEA of Test case3

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component 1</td>
<td>Failure Mode 3</td>
<td>Affect component 2</td>
<td>Low effect</td>
<td>None</td>
<td>Low</td>
<td>Moderately High</td>
<td>12</td>
<td>Message3 from Comp3to1_MessageRecv</td>
</tr>
<tr>
<td>Component 2</td>
<td>Failure Mode 1</td>
<td>Affect other component</td>
<td>Affect the system</td>
<td>None</td>
<td>High</td>
<td>Moderate</td>
<td>35</td>
<td>Message1 from Comp1to2_MessageRecv</td>
</tr>
<tr>
<td>Failure Mode 4</td>
<td>Moderate effect on other component</td>
<td>Affect the system</td>
<td>Moderate</td>
<td>Beyond Moderate</td>
<td>Almost Certain</td>
<td>30</td>
<td>Message4 from Comp1to2_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Failure Mode 6</td>
<td>Affect other component</td>
<td>Moderate effect on the system</td>
<td>Very Low</td>
<td>Remote</td>
<td>Low</td>
<td>24</td>
<td>Message6 from Comp3to2_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Component 3</td>
<td>Failure Mode 2</td>
<td>Affect component 1</td>
<td>Low</td>
<td>None</td>
<td>Moderately High</td>
<td>Almost Certain</td>
<td>6</td>
<td>Message2 from Comp2to3_MessageRecv</td>
</tr>
<tr>
<td>Failure Mode 5</td>
<td>Affect other component</td>
<td>Shut down the system</td>
<td>Hazard With Warning</td>
<td>Moderate</td>
<td>Almost Certain</td>
<td>36</td>
<td>Message5 from Comp2to3_MessageRecv</td>
<td></td>
</tr>
</tbody>
</table>

#### 5.1.4 Test Case4

Here we carry out the testing of the transformation process to determine how well it transforms a source model with more than one interaction (sequence diagram).
Figure 5-7 Test Case 3 Composite Structure Diagram

Figure 5-8 Test Case 4 Sequence diagram
Table 5-5 FMEA table for Test Case 4

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RP N Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component5</td>
<td>Failure Mode 3</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message13 From Com4to5_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Failure Mode 6</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message17 From Com4to5 in CombFrag_MessageRecv</td>
</tr>
<tr>
<td>Component4</td>
<td>Failure Mode 2</td>
<td>Affects Component 4</td>
<td>None</td>
<td>None</td>
<td>Low</td>
<td>Almost Certain</td>
<td>3</td>
<td>Message12 From Com2to4_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Failure Mode 6</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message16 From Com2to4 in CombFrag_MessageRecv</td>
</tr>
<tr>
<td>Component1</td>
<td>Failure Mode 8</td>
<td>Low effect on other component</td>
<td>Low</td>
<td>High</td>
<td>Remote</td>
<td>Very High</td>
<td>14</td>
<td>Message2 From Comp2to1_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Failure Mode</td>
<td>Low effect on others</td>
<td>No visible</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message5 From Comp2to1 in</td>
</tr>
</tbody>
</table>
5.1.5 Test Case 5

At this stage the aim is to test the transformation process ability to transform more than one source element (both structural and interaction model elements). So the source model here consists of a simple sequence diagram and a composite structural diagram as shown in the diagram below.
Figure 5-10 Test Case 5 Composite Structure Diagram

Figure 5-11 Test Case 5 Sequence Diagram
<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component1</td>
<td>CS Failure Mode 2</td>
<td>Affects Component 2</td>
<td>None</td>
<td>None</td>
<td>High</td>
<td>Almost Certain</td>
<td>7</td>
<td>InformationItem m3 from Comp2to1</td>
</tr>
<tr>
<td></td>
<td>CS Failure Mode 5</td>
<td>Affect Component 3</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>InformationItem m5 from Comp3to1</td>
</tr>
<tr>
<td>Failure Mode 3</td>
<td>Affect Component 3</td>
<td>Low effect on the system</td>
<td>None</td>
<td>Very High</td>
<td>Almost Certain</td>
<td>8</td>
<td>Message3 from Comp3to1_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Component2</td>
<td>CS Failure Mode 1</td>
<td>Low effect on others</td>
<td>Moderate effect on the system</td>
<td>None</td>
<td>Low</td>
<td>Very Low</td>
<td>21</td>
<td>InformationItem m1 from Comp1to2</td>
</tr>
<tr>
<td></td>
<td>CS Failure Mode 4</td>
<td>Affect other components</td>
<td>Low effect on the system</td>
<td>Low</td>
<td>Remote</td>
<td>High</td>
<td>15</td>
<td>InformationItem m6 from Comp3to2</td>
</tr>
<tr>
<td>Failure Mode 1</td>
<td>Low effect on other component</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message1 from Class1to2_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Failure Mode 5</td>
<td>Minor effect</td>
<td>Moderate effect</td>
<td>Very Low</td>
<td>Remote</td>
<td>Low</td>
<td>24</td>
<td>Message5 from Comp3to2_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Component3</td>
<td>CS Failure Mode 5</td>
<td>Affect other component</td>
<td>Low Effect</td>
<td>Very High</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>8</td>
<td>InformationItem m2 from Comp1to3</td>
</tr>
<tr>
<td></td>
<td>CS Failure Mode 3</td>
<td>Affects Others</td>
<td>High effects on the system</td>
<td>Low</td>
<td>High</td>
<td>Almost Certain</td>
<td>35</td>
<td>InformationItem m4 from Comp2to3</td>
</tr>
<tr>
<td>Failure Mode 2</td>
<td>Low effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Moderate</td>
<td>5</td>
<td>Message2 from Comp2to3_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Failure Mode 4</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message4 from Comp1to3_MessageRecv</td>
<td></td>
</tr>
</tbody>
</table>

5.1.6 Test Case 6

This include the combination of all the previous test cases in one source model (all the possible source model features) that is, more than one sequence diagram with combined fragments and a composite structure diagram to test the completeness of the
transformation process and its capability to transform every possible source model elements in one source model (input features)

Figure 5-12 Test Case6 Composite Diagram
Figure 5-13 Test Case 6 Sequence diagram1

Figure 5-14 Test Case 6 Sequence diagram2
<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component1</td>
<td>Failure Model1 of Component 1</td>
<td>Affects Component 2</td>
<td>No effect</td>
<td>Low</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>5</td>
<td>Info to Component 1</td>
</tr>
<tr>
<td></td>
<td>Failure Mode2 of Component 1</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message3 from Comp3to1_MessageRecv</td>
</tr>
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<td></td>
<td>Failure Mode3 of Component 1</td>
<td>Affects the next component</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Remote</td>
<td>8</td>
<td>Message6 from Comp2to1_MessageRecv</td>
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<td></td>
<td>Failure Mode4 of Component 1</td>
<td>Affect component 3</td>
<td>Low effect on the system</td>
<td>Low</td>
<td>Remote</td>
<td>Remote</td>
<td>40</td>
<td>Message8 from Comp3to1_MessageRecv</td>
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<td>Failure Mode5 of Component 1</td>
<td>Affects component 2</td>
<td>Low effect</td>
<td>None</td>
<td>Beyond Moderate</td>
<td>Almost Certain</td>
<td>5</td>
<td>Message16 from Comp2to1_MessageRecv</td>
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<td>Component2</td>
<td>Failure Mode1 of Component 2</td>
<td>Affect Other component</td>
<td>High</td>
<td>Very Low</td>
<td>Extremely High</td>
<td>Low</td>
<td>216</td>
<td>Info from comp1to2</td>
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<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
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<td>Info from Comp5to2</td>
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<td>Failure Mode3 of Component 2</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Moderate</td>
<td>5</td>
<td>Message1 from Comp1to2_MessageRecv</td>
</tr>
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<td>Failure Mode4 of Component 2</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message5 from Comp1to2_MessageRecv</td>
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<tr>
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<td>Failure Mode5 of Component 2</td>
<td>Affect other component</td>
<td>Affects the system</td>
<td>None</td>
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<td>Low</td>
<td>54</td>
<td>Message11 from Comp1to2_MessageRecv</td>
</tr>
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<td>Low effect</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
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<td>Message15 from Comp5to2_MessageRecv</td>
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<td>Component3</td>
<td>Failure Mode1 of Component 3</td>
<td>No effect</td>
<td>Low Effect</td>
<td>Low</td>
<td>Beyond Moderate</td>
<td>Almost Certain</td>
<td>25</td>
<td>Info from Comp1to3</td>
</tr>
<tr>
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<td>Failure Mode2 of Component 3</td>
<td>Affects others</td>
<td>No Effect</td>
<td>None</td>
<td>Very High</td>
<td>Moderate</td>
<td>40</td>
<td>Info from Comp4to3</td>
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<td>Affect Component 2</td>
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<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message2 from Comp2to3_MessageRecv</td>
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<td>Affect other components</td>
<td>No effect on the system</td>
<td>High</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>Message from Component</td>
<td>Message Type</td>
</tr>
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<td>------</td>
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<td>---------------</td>
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<tr>
<td>Component 3</td>
<td>Failure Mode 4 of Component 3</td>
<td>Affect component 2</td>
<td>No effect on the system</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>7</td>
<td>Message4 from Comp1to3_Messa geRecv</td>
</tr>
<tr>
<td>Component 3</td>
<td>Failure Mode 5 of Component 3</td>
<td>Affect component 5</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message7 from Comp1to3_Messa geRecv</td>
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<td>Failure Mode 6 of Component 3</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message13 from Comp3to5_Messa geRecv</td>
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<td>Component 4</td>
<td>Failure Mode 2 of Component 4</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Info from Comp1to4</td>
</tr>
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<td>Failure Mode 1 of Component 4</td>
<td>High effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Info from Comp2to4</td>
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<td>Component 4</td>
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<td>No effect on the system</td>
<td>High</td>
<td>Remote</td>
<td>High</td>
<td>21</td>
<td>Info from Comp3to4</td>
</tr>
<tr>
<td>Component 4</td>
<td>Failure Mode 5 of Component 4</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Info from Comp3to4</td>
</tr>
<tr>
<td>Component 4</td>
<td>Failure Mode 6 of Component 4</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>High</td>
<td>Almost Certain</td>
<td>7</td>
<td>Message4 from Comp3to4_Messa geRecv</td>
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<tr>
<td>Component 5</td>
<td>Failure Mode 4 of Component 5</td>
<td>Affects others</td>
<td>Affect the system</td>
<td>Very High</td>
<td>High</td>
<td>Almost Certain</td>
<td>56</td>
<td>Info from Comp1to5</td>
</tr>
<tr>
<td>Component 5</td>
<td>Failure Mode 1 of Component 5</td>
<td>None</td>
<td>Moderat e effect</td>
<td>None</td>
<td>High</td>
<td>Very Low</td>
<td>49</td>
<td>Info from Comp3to5</td>
</tr>
<tr>
<td>Component 5</td>
<td>Failure Mode 2 of Component 5</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Info from Comp2to5</td>
</tr>
<tr>
<td>Component 5</td>
<td>Failure Mode 3 of Component 5</td>
<td>None</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Info from Comp3to5</td>
</tr>
<tr>
<td>Component 5</td>
<td>Failure Mode 5 of Component 5</td>
<td>Affects Component 2</td>
<td>Affects the System</td>
<td>Minor</td>
<td>Remote</td>
<td>Very Low</td>
<td>21</td>
<td>Message12 from Comp2to5_Messa geRecv</td>
</tr>
<tr>
<td>Component 5</td>
<td>Failure Mode 6 of Component 5</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Message14 from Comp3to5_Messa geRecv</td>
</tr>
</tbody>
</table>
5.2 Case Study1 (LCS)

This case study is taken from [DAV10], where the authors present a UML/SysML model of Level Control System (LCS) system, and derived its FMEA model. The decision to use a case study built by someone else is in order to reduce the “author bias” in method/project development, in which self-built test cases by a software developer may be too selective (willingly or unwillingly). The case-study contains both sequence and composite structure diagram as the input (Source model) unlike the author’s approach with the use of SysML for the design and description of the system architecture and behavior, as well as their algorithms for the FMEA generation.

As described in [DAV10] the LCS is mounted on a tank filled with an unspecified fluid and fluid level. The basic responsibility of the LCS is to insure that the level of the fluid in the tank will never exceed the capacity of the tank. The components of LCS include; two electrovalves (Ev1, Ev2) connected upstream of the tank, two mechanical valves (Mv1, Mv2), two level sensors (S1, S2) command the electrovalves and one Alarm (Al). The LCS working principle can be described as follows: “If S1 detects a too high level of fluid in the tank, it closes Ev1. If S2 detects a too high level, it closes Ev2 and activates Al. When Al rings, an operator closes Mv1. If the fluid level is still too high after 3 min, the operator opens Mv2 that drains the tank”. Figure 5-1 and 5-2 presents the annotated UML Composite structure and Sequence diagram of the system, respectively, and Table 5-8 shows the FMEA table derived by our transformation.
Figure 5-15 the case study 1 (LCS) Composite Structure Diagram

Figure 5-16 Case study1 (LCS) Sequence diagram
<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
<td>Wrong movement</td>
<td>Incorrect validation</td>
<td>System error</td>
<td>Low</td>
<td>Moderate</td>
<td>Almost Certain</td>
<td>20</td>
<td>Stable movement_Messa geRecv</td>
</tr>
<tr>
<td>Sensor S1</td>
<td>No detection</td>
<td>Effect On Ev1 through CiS1-CiEv1 [CommandInterface], On Ev1 by CommandEv</td>
<td>Internal effect and affects the system smooth runnings</td>
<td>Very High</td>
<td>Moderate</td>
<td>Almost Certain</td>
<td>32</td>
<td>PiS1:PowerInput</td>
</tr>
<tr>
<td>False detection</td>
<td>Effect On Ev1 through CiS1-CiEv1 [CommandInterface], On Ev1 by CommandEv</td>
<td>Internal effect and affects the system smooth runnings</td>
<td>Very High</td>
<td>Beyond Moderate</td>
<td>Moderat e</td>
<td>40</td>
<td>Activation_Messa geRecv</td>
<td></td>
</tr>
<tr>
<td>Sensor S2</td>
<td>PiS2 Power failure</td>
<td>No invert state signal sent</td>
<td>The system sensor not respondiing</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>PiS2:PowerInput</td>
</tr>
<tr>
<td></td>
<td>No activation signal</td>
<td>Electro valves remain closed</td>
<td>System activation error</td>
<td>Hazard With Warning</td>
<td>Remote</td>
<td>9</td>
<td>Activation_Messa ge0Recv</td>
<td></td>
</tr>
<tr>
<td>Electro Valve EV1</td>
<td>No PiEV1 power detection</td>
<td>No signal to EV2</td>
<td>System shutdown /hangs</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>PiEV1:PowerInput</td>
</tr>
<tr>
<td>Wrong command dCiEV1</td>
<td>Wrong signal to EV2</td>
<td>System error</td>
<td>High</td>
<td>Remote</td>
<td>Low</td>
<td>42</td>
<td>CiEV1:CommandInterface</td>
<td></td>
</tr>
<tr>
<td>No Fluid detected</td>
<td>EV1 remain closed</td>
<td>System not responding</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>InEV1:Fluid</td>
<td></td>
</tr>
<tr>
<td>Inaccurate Comma nd EV</td>
<td>EV1 invert state error</td>
<td>System output error</td>
<td>Very High</td>
<td>Remote</td>
<td>Low</td>
<td>48</td>
<td>CommandEv_Mes sageRecv</td>
<td></td>
</tr>
<tr>
<td>Stuck opened</td>
<td>On LCS through InEv1-In1LCS [Fluid] On Ev2 through OutEv1-InEv2 [Fluid] On Ev1 by InvertState</td>
<td>Affects the system's running</td>
<td>Minor</td>
<td>Extremely High</td>
<td>Almost Certain</td>
<td>27</td>
<td>InvertState_Messa geRecv</td>
<td></td>
</tr>
<tr>
<td>Electro Valve EV2</td>
<td>PiEV2 Power failure</td>
<td>No output signal sent</td>
<td>System output failure</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>PiEV2:PowerInput</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>------</td>
<td>--------</td>
<td>----------------</td>
<td>---</td>
<td>-----------------</td>
</tr>
<tr>
<td>Failed CiEV2 detect ion</td>
<td>No reply signal to EV1</td>
<td>System output failure</td>
<td>None</td>
<td>Low</td>
<td>Low</td>
<td>18</td>
<td>CiEV2:CommandInterface</td>
<td></td>
</tr>
<tr>
<td>No Fluid detected</td>
<td>EV1 remain open</td>
<td>System output error</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>InEV2:Fluid</td>
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</tr>
<tr>
<td>Ev command error</td>
<td>Affects the other</td>
<td>System output error</td>
<td>Very High</td>
<td>Moderate</td>
<td>Low</td>
<td>192</td>
<td>CommandEV_MessageRecv</td>
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</tr>
<tr>
<td>Inaccurate state inversion</td>
<td>Affects the other components</td>
<td>System output error</td>
<td>Minor</td>
<td>High</td>
<td>Almost Certain</td>
<td>21</td>
<td>InvertState_Message0Recv</td>
<td></td>
</tr>
<tr>
<td>Mechanical Valve MV1</td>
<td>Stuck</td>
<td>Affects immediate components</td>
<td>Affects the system</td>
<td>Low</td>
<td>Remote</td>
<td>Low</td>
<td>30</td>
<td>InMV1:Fluid</td>
</tr>
<tr>
<td>Inaccurate actuator signal</td>
<td>Affects the system alarm</td>
<td>System unstable</td>
<td>Very Low</td>
<td>Moderately High</td>
<td>Very Low</td>
<td>168</td>
<td>ActuatorMV1</td>
<td></td>
</tr>
<tr>
<td>No invert signal received</td>
<td>Affect other components</td>
<td>System continue in the same state</td>
<td>Very High</td>
<td>Very Low</td>
<td>Almost Certain</td>
<td>16</td>
<td>InvertState_Message1Recv</td>
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</tr>
<tr>
<td>Mechanical Valve MV2</td>
<td>Inaccurate MV2 actuator</td>
<td>Wrong alarm signal</td>
<td>System unstable</td>
<td>Hazard With Warning</td>
<td>Remote</td>
<td>Low</td>
<td>54</td>
<td>ActuatorMV2</td>
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<tr>
<td>Wrong invert signal</td>
<td>Affects others</td>
<td>The system receives wrong inversion</td>
<td>None</td>
<td>High</td>
<td>High</td>
<td>21</td>
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<td>alarm AL</td>
<td>PiAL2 Power failure</td>
<td>Affects the system alarm sub-system's</td>
<td>Bad system alarm</td>
<td>Very High</td>
<td>Remote</td>
<td>Low</td>
<td>48</td>
<td>PiAL:PowerInput</td>
</tr>
<tr>
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<td>Affects the system</td>
<td>Affects other components</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>CiAL:CommandInterface</td>
<td></td>
</tr>
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<td>Wrong alarm signal</td>
<td>Affects the system speaker</td>
<td>Bad system alarm</td>
<td>None</td>
<td>Low</td>
<td>Moderately</td>
<td>3</td>
<td>Speaker:Speaker</td>
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<td>Wrong command alarm signal</td>
<td>Affects the operator and the alarm sub-system</td>
<td>Wrong system alarm</td>
<td>High</td>
<td>Very Low</td>
<td>Almost Certain</td>
<td>14</td>
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<td>Wrong invert signal</td>
<td>Shuts the alarm</td>
<td>The system alarm shutdown</td>
<td>Low</td>
<td>Moderate</td>
<td>Very Low</td>
<td>140</td>
<td>InvertAlarmState_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>No validation signal detected</td>
<td>Affects the Alarm</td>
<td>Lack of proper alarm system</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>63</td>
<td>ValidatingAlarm_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>No invert alarm</td>
<td>Affects other alarm sub-system</td>
<td>Wrong system alarm</td>
<td>High</td>
<td>High</td>
<td>Almost Certain</td>
<td>49</td>
<td>InvertAlarmState_MessageRecv</td>
<td></td>
</tr>
</tbody>
</table>
5.3 Case study-2 (TER)

This example from [GUI03] is the second case study from literature used to validate this thesis work. The Tele-echography (TER) system allows an expert physician (operator) to move or adjust by hand a scanner virtual probe in an unconstrained way, and in turn safely reproduces this adjustment/movement on the distant robotic remote site where the patient is located. This gives the operator the liberty to move the virtual probe to control the remote one on the patient. The risk analysis was presented with using Failure Modes Effects and Critically Analysis (FMECA).

![Composite diagram](image1)

**Figure 5-17 Case Study2 Composite diagram**

![Sequence diagram](image2)

**Figure 5-18 Case study2 (TER) Sequence Diagram1**
Figure 5-19 Case study2 (TER) Sequence Diagram2

Figure 5-20 Case study2 (TER) Sequence Diagram3
<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Detection</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Localizer</td>
<td>Mis-interpretation of 3D position</td>
<td>Wrong signal</td>
<td>System fails</td>
<td>None</td>
<td>Extremely High</td>
<td>High</td>
<td>27</td>
<td>Read 3D Position_MessageRecv</td>
</tr>
<tr>
<td>Error reading 3D position</td>
<td>No signal</td>
<td>No response</td>
<td>Very High</td>
<td>Remote</td>
<td>Low</td>
<td></td>
<td>48</td>
<td>Read 3D Position_Message0Recv</td>
</tr>
<tr>
<td>Mis-interpretation of 3D position</td>
<td>No signal</td>
<td>No response</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td></td>
<td>1</td>
<td>Read 3D Position_Message1Recv</td>
</tr>
<tr>
<td>3D Sensor</td>
<td>Wrong Movement of 3D</td>
<td>Error in calculation</td>
<td>Incorrect response</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Move 3D sensor on Patient Body_MessageRecv</td>
</tr>
<tr>
<td>Error during localization</td>
<td>Affect other components</td>
<td>Localization effect on the system</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td></td>
<td>1</td>
<td>Localize_MessageRecv</td>
</tr>
<tr>
<td>Wrong 3D movement</td>
<td>Wrong calculation</td>
<td>System crash</td>
<td>Low</td>
<td>High</td>
<td>Almost Certain</td>
<td>35</td>
<td>Move 3D Sensor on patient Body_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>No Position signal</td>
<td>No effect</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Very Low</td>
<td></td>
<td>7</td>
<td>Localize_Message0Recv</td>
</tr>
<tr>
<td>Wrong 3D Movement</td>
<td>Incorrect response</td>
<td>No effect</td>
<td>None</td>
<td>Remote</td>
<td>Low</td>
<td></td>
<td>6</td>
<td>Move 3D Sensor on patient Body_Message0Recv</td>
</tr>
<tr>
<td>Operator</td>
<td>Wrong representation of the patient</td>
<td>Wrong interpretation by the operator</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>3D representation Of Patient_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Bad 3D sensor manipulation</td>
<td>Bad Patient Model</td>
<td>Pressure on the Patient too high</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Bad Indication_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>HMI</td>
<td>Wrong Signal</td>
<td>Incorrect calibration</td>
<td>Wrong output</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Start Calibrate patient Model_MessageRecv</td>
</tr>
<tr>
<td>Invisible Patient Model</td>
<td>Loss of signals</td>
<td>No response</td>
<td>Very High</td>
<td>Remote</td>
<td>Moderate</td>
<td></td>
<td>8</td>
<td>Show Patient Model_MessageRecv</td>
</tr>
<tr>
<td>Wrong input</td>
<td>Invalid update</td>
<td>Wrong output</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Validate_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>HMI failure</td>
<td>Affects the operator input signal</td>
<td>Wrong output</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>HMI alternative failure cause_MessageRecv</td>
<td></td>
</tr>
<tr>
<td>Motion Planner</td>
<td>Failed Motion Planner</td>
<td>No response</td>
<td>System hangs</td>
<td>None</td>
<td>Remote</td>
<td>Almost Certain</td>
<td>1</td>
<td>Motion Planner failure cause_MessageRecv</td>
</tr>
</tbody>
</table>
Table 5-8 The FMEA Table For Case Study2 (Continued)

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure mode</th>
<th>Local Effect</th>
<th>System Effect</th>
<th>Severity</th>
<th>Detection</th>
<th>Detection</th>
<th>RPN Value</th>
<th>Failure Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>TELEOP Controller</td>
<td>Wrong Control signal</td>
<td>Wrong signal</td>
<td>Wrong output</td>
<td>Low</td>
<td>Low</td>
<td>Almost</td>
<td>15</td>
<td>Control in a position_MessageRecv</td>
</tr>
<tr>
<td>Loss of control</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
<td>Remote</td>
<td>Almost</td>
<td>Certain</td>
<td>18</td>
<td>Control in a position_Message0Recv</td>
</tr>
<tr>
<td>Geometrical model</td>
<td>Wrong Calculation</td>
<td>High</td>
<td>Low</td>
<td>Very</td>
<td>Remote</td>
<td>Very</td>
<td>72</td>
<td>Calculate_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Failed length Calculation</td>
<td>High</td>
<td>None</td>
<td>None</td>
<td>Remote</td>
<td>Almost</td>
<td>1</td>
<td>Calculate length_MessageRecv</td>
</tr>
<tr>
<td>Position Controller</td>
<td>Loss of signal regulation</td>
<td>Severe effect</td>
<td>High</td>
<td>None</td>
<td>Remote</td>
<td>Almost</td>
<td>1</td>
<td>Regulate_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Loss of signal regulation</td>
<td>Very high</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>20</td>
<td>Regulate_Message0Recv</td>
</tr>
<tr>
<td></td>
<td>Loss of signal regulation</td>
<td>Extremel y high</td>
<td>High</td>
<td>None</td>
<td>Remote</td>
<td>Almost</td>
<td>1</td>
<td>Regulate_Message1Recv</td>
</tr>
<tr>
<td>Robot Model</td>
<td>Failed signal to read</td>
<td>Low</td>
<td>None</td>
<td>Low</td>
<td>Remote</td>
<td>Almost</td>
<td>5</td>
<td>Read_MessageRecv</td>
</tr>
<tr>
<td>Patient Model</td>
<td>Wrong Number Points</td>
<td>Affects HMI</td>
<td>Affects system smooth running</td>
<td>Moderat e</td>
<td>Remote</td>
<td>Almost</td>
<td>6</td>
<td>Create (Number of Points)_MessageRecv</td>
</tr>
<tr>
<td></td>
<td>Wrong Calculation</td>
<td>Wrong signal to the other components</td>
<td>Wrong output</td>
<td>Hazard With Warning</td>
<td>Almost Certain</td>
<td>Almost Certain</td>
<td>90</td>
<td>Calculate Model_MessageRecv</td>
</tr>
<tr>
<td>Read wrong signal</td>
<td>Wrong input</td>
<td>Wrong response</td>
<td>None</td>
<td>Remote</td>
<td>Almost</td>
<td>Certain</td>
<td>1</td>
<td>Read_Message0Recv</td>
</tr>
</tbody>
</table>
6 Chapter: Conclusions

6.1.1 Achievements

This thesis has successfully proposed, implemented, and verified/validated a multi-step process for model to model transformations using the Epsilon transformation language family (ETL+EOL) and the text-to-text transformation language XSLT, in which the transformation input, a UML software model with failure mode annotations is transformed into a target FMEA tabular model. The source model is composed of composite structure diagrams and sequence diagrams with applied Fmode stereotypes.

Papyrus [PAP15] is the UML modeling tool used in this work. We selected Papyrus because it is an open source tool based on the Eclipse environment, supported by PolarSys [Pola16], an Eclipse Industry Working Group created by large industry players and tool providers working together on the creation and support of Open Source tools for the model-driven development of embedded systems. Another reason we selected Papyrus was because the Epsilon engine is able to directly accept the Papyrus annotated UML models as source models. The transformation accepts the standard UML metamodel, but also require a target metamodel for the FMEA domain, which is not standardized; we had to define it with a special metamodeling language named Emphatic, provided by the Eclipse platform. With the use of the FMEA metamodel, ETL was able to generate an XMI file of the target model, which could then be transformed to an FMEA table in text format by an XSLT text-to-text transformation.

6.1.2 Limitations

The transformation implementation has some limitations, as follows. The transformation accepts only UML source models built as described in Chapter 3. If the source model
does not follow the modeling style presented in Chapter 3, the transformation stops running.

Another limitation is that, the UML editor used in this work, Papyrus, does not yet implement all the metaclasses defined in the UML metamodel at the time of this thesis implementation. E.g., in deployment diagrams it is not easy to model communication networks because the links between deployment nodes are not implemented. During our modeling it was also discovered that Papyrus does not support the use of connector between ports of the classes in the composite structure diagram. The sequence diagram’s lifelines could only represent properties in the composite structure diagram.

The number of existing works that use a model-driven approach for building FMEA tables is very limited. We searched very hard the literature to find examples of FMEA analysis applied in an MDD context, in order to extend the set of our test cases with models created by other authors. The goal was to reduce the potential “author bias” in the project or implementation testing when creating test cases.

This work is based on just the traditional FMEA, which can as well be extended to the Failure Mode, Effect and Critical Analysis (FMECA) version.

FMEA is an induction safety analysis (bottom-up) approach that can be combined with Fault-Tree Analysis (FTA), which is a deductive analysis (top-down) approach. We have not done this in the thesis, proposing it as a direction for future work.

Due to all the mentioned limitations our implementation experienced some difficulties. However, we were able to design solutions to deal with some of the limitations and left some others as future work.
6.1.3 Directions for Future Work

The transformation process of UML+Fmode models to FMEA models developed in this thesis can be further developed in the following directions:

- As shown in the FMEA multi-step process approach for this work, the generation of FMEA table requires another level of transformation (Text2Text) using XSLT to generate the FMEA table. It would be of a great benefit to the user if all these steps could be integrated into one single script which does not require manual intervention of the user to go from one step to another.

- The transformation could be extended from the generated FMEA to other alternatives, such as FMECA.

- The UML editor Papyrus used in this implementation is evolving quickly. The transformation should be updated to include the new features supported by the tool as they become available.

- The development of more pre-transformation verifications processes of the input model to verify the correctness and completeness of the model before the transformation in order to avoid problems or errors would make the transformation more user friendly.

- The FMEA analysis could be combined with Fault-Tree Analysis (FTA), both in the context of model-driven development.
Appendices

Appendix A

A.1 Running Example: XML Target Model

```xml
<?xml version="1.0" encoding="ASCII"?>
<System xmi:version="2.0"
xmi:namespace="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of model">
  <component name="Sensor/>
  <component name="Input Control Circuit">
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="Sensor Analogue output signal "/>
    </failuremode>
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="Convert Position_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Micro-Controller">
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="Initialize Input Pin Register_MessageRecv"/>
    </failuremode>
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="Get value_MessageRecv"/>
    </failuremode>
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="Compute Duty Cycle_MessageRecv"/>
    </failuremode>
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="PWM Period_MessageRecv"/>
    </failuremode>
  </component>
  <component name="ISR">
    <failuremode name="" FailureLocalEffect=""
SystemFailureLevelEffect="" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
      <failurecause name="ADC value"/>
    </failuremode>
  </component>
</System>
```
A.2  Case Study 1: XML Target Model

This is Appendix A, Sub-Appendix 2

<?xml version="1.0" encoding="ASCII"?>
<System xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of model">
  <component name="Operator">
    <failuremode name="Wrong movement" FailureLocalEffect="Incorrect validation" SystemFailureLevelEffect="system error" severity="Low" occurrence="Moderate" detection="AlmostCertain" RPN="20">
      <failurecause name="Stable movement_MessageRecv"/>
    </failuremode>
    <failuremode name="Initialize Output pin_MessageRecv"/>
  </component>
  <failuremode name="Remote" FailureLocalEffect="" SystemFailureLevelEffect="" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Initialize ISR_MessageRecv"/>
  </failuremode>
  <component name="Fan">
    <failuremode name="regulate Speed_MessageRecv"/>
  </component>
  <component name="Ball">
    <failuremode name="Position_MessageRecv"/>
  </component>
  <component name="Output Control Circuit">
    <failuremode name="Initialize Output pin_MessageRecv"/>
    <failuremode name="OutPut signal pin_MessageRecv"/>
  </component>
</System>
</failuremode>
</component>

<component name="Sensor S1">

<failuremode name="No detection" FailureLocalEffect="Effect On Ev1 through CiS1-CiEv1\&#x26;[CommandInterface], On Ev1 by CommandEv\&#x26;On S1 by Activation"
SystemFailureLevelEffect="Internal effect and affects the system smooth runnings" severity="VeryHigh" occurrence="Moderate"
detection="AlmostCertain" RPN="32">
    <failurecause name="PiS1:PowerInput"/>
</failuremode>

<failuremode name="False detection" FailureLocalEffect="Effect On Ev1 through CiS1-CiEv1\&#x26;[CommandInterface], On Ev1 by CommandEv\&#x26;On S1 by Activation"
SystemFailureLevelEffect="Internal effect and affects the system smooth runnings" severity="VeryHigh" occurrence="BeyondModerate"
detection="Moderate" RPN="40">
    <failurecause name="Activation_MessageRecv"/>
</failuremode>
</component>

<component name="Sensor S2">

<failuremode name="PiS2 Power failure" FailureLocalEffect="No invert state signal sent" SystemFailureLevelEffect="The system sensor not responding" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
    <failurecause name="PiS2:PowerInput"/>
</failuremode>

<failuremode name="No activation signal"
FailureLocalEffect="Electro valves remain closed"
SystemFailureLevelEffect="System activation error" severity="HazardWithWarning" occurrence="Remote"
detection="Moderate" RPN="9">
    <failurecause name="Activation_Message0Recv"/>
</failuremode>
</component>

<component name="Electro Valve EV1">

<failuremode name="No PiEV1 power detection" FailureLocalEffect="No signal to EV2"
SystemFailureLevelEffect="System shutdown/ hangs\&#x26; System error"
severity="None" occurrence="Remote" detection="AlmostCertain"
RPN="1">
    <failurecause name="PiEV1:PowerInput"/>
</failuremode>

<failuremode name="Wrong commandCiEV1" FailureLocalEffect="Wrong signal to EV2" SystemFailureLevelEffect="System error"
severity="High" occurrence="Remote" detection="Low" RPN="42">
    <failurecause name="CiEV1:CommandInterface"/>
</failuremode>

<failuremode name="No Fluid detected" FailureLocalEffect="EV1 remain closed" SystemFailureLevelEffect="System not responding"
severity="None" occurrence="Remote" detection="AlmostCertain"
RPN="1">
    <failurecause name="InEV1:Fluid"/>
</failuremode>
</component>
<failuremode name="Inaccurate CommandEV" FailureLocalEffect="EV1 invert state error" SystemFailureLevelEffect="System output error" severity="VeryHigh" occurrence="Remote" detection="Low" RPN="48">
  <failurecause name="CommandEV_MessageRecv"/>
</failuremode>

<failuremode name="Stuck opened" FailureLocalEffect="On LCS through InEv1-In1LCS&amp;xD;[Fluid] On Ev2 through OutEv1-InEv2&amp;xD;[Fluid] On Ev1 by InvertState" SystemFailureLevelEffect="Affects the system's runnings&amp;xA;" severity="Minor" occurrence="ExtremelyHigh" detection="AlmostCertain" RPN="27">
  <failurecause name="InvertState_MessageRecv"/>
</failuremode>

<component name="Electro Valve EV2">
  <failuremode name="PiEV2 Power failure" FailureLocalEffect="No output signal sent" SystemFailureLevelEffect="System output failure" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="PiEV2:PowerInput"/>
  </failuremode>
  <failuremode name="Failed CiEV2 detection" FailureLocalEffect="No reply signal to EV1" SystemFailureLevelEffect="System output error" severity="None" occurrence="Low" detection="AlmostCertain" RPN="18">
    <failurecause name="CiEV2:CommandInterface"/>
  </failuremode>
  <failuremode name="No Fluid detected" FailureLocalEffect="EV1 remain open" SystemFailureLevelEffect="System error" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="InEV2:Fluid"/>
  </failuremode>
  <failuremode name="Ev command error" FailureLocalEffect="Affects the other" SystemFailureLevelEffect="System output error" severity="VeryHigh" occurrence="Moderate" detection="Low" RPN="192">
    <failurecause name="CommandEV_MessageRecv"/>
  </failuremode>
  <failuremode name="Inaccurate state inversion" FailureLocalEffect="affects the other components" SystemFailureLevelEffect="System output error" severity="Minor" occurrence="High" detection="AlmostCertain" RPN="21">
    <failurecause name="InvertState_Message0Recv"/>
  </failuremode>
</component>

<component name="Mechanical Valve MV1">
  <failuremode name="Stucked" FailureLocalEffect="Affects immediate components" SystemFailureLevelEffect="Affects the system" severity="Low" occurrence="Remote" detection="Low" RPN="30">
    <failurecause name="InMV1:Fluid"/>
  </failuremode>
  <failuremode name="Inaccurate actuator signal" FailureLocalEffect="Affects the system alarm " SystemFailureLevelEffect="System unstable " severity="VeryLow" occurrence="ModeratelyHigh" detection="VeryLow" RPN="168">
<failurecause name="ActuatorMV1"/>
</failuremode>

<failuremode name="No invert signal received"
FailureLocalEffect="Affect other components"
SystemFailureLevelEffect="system continue in the same state"
severity="VeryHigh" occurrence="VeryLow" detection="AlmostCertain"
RPN="16">
  <failurecause name="InvertState_Message1Recv"/>
</failuremode>

<component name="Mechanical Valve MV2">
  <failuremode name="Inaccurate MV2 actuator"
FailureLocalEffect="wrong alarm signal"
SystemFailureLevelEffect="System unstable"
severity="HazardWithWarning" occurrence="Remote" detection="Low"
RPN="54">
    <failurecause name="ActuatorMV2"/>
  </failuremode>
  <failuremode name="Wrong invert signal"
FailureLocalEffect="affects others" SystemFailureLevelEffect="The system receives wrong inversion" severity="None" occurrence="High" detection="High" RPN="21">
    <failurecause name="InvertState_Message2Recv"/>
  </failuremode>
</component>

<component name="alarm AL">
  <failuremode name="PiAL2 Power failure"
FailureLocalEffect="Affects the system alarm sub-system's"
SystemFailureLevelEffect="Bad system alarm" severity="VeryHigh"
occurrence="Remote" detection="Low" RPN="48">
    <failurecause name="PiAL:PowerInput"/>
  </failuremode>
  <failuremode name="Wrong alarm signal"
FailureLocalEffect="Affects the system speaker"
SystemFailureLevelEffect="bad system alarm" severity="None"
occurrence="Low" detection="Moderate" RPN="3">
    <failurecause name="Speaker:Speaker"/>
  </failuremode>
  <failuremode name="Wrong command alarm signal"
FailureLocalEffect="Affects the operator and the alarm sub-system"
SystemFailureLevelEffect="wrong system alarm" severity="High"
occurrence="VeryLow" detection="AlmostCertain" RPN="14">
    <failurecause name="CommandAlarm_MessageRecv"/>
  </failuremode>
  <failuremode name="Wrong invert signal"
FailureLocalEffect="shuts the alarm" SystemFailureLevelEffect="The system alarm shutdown" severity="Low" occurrence="Moderate" detection="VeryLow" RPN="140">
    <failurecause name="InvertAlarmState_MessageRecv"/>
  </failuremode>
</component>
A.3 Case Study 2: XML Target Model

<?xml version="1.0" encoding="ASCII"?>
<xml:xmi version="2.0"
xmi:mr:version="2.0"
xmns:xmi="http://www.omg.org/XMI" xmlns="FMEA">
  <System name="FMEA of TEERModel"/>
  <component name="Localizer">
    <failuremode name="mis-interpretation of 3D position"
      FailureLocalEffect="Wrong signal" SystemFailureLevelEffect="System fails"
      severity="None" occurrence="ExtreemlyHigh" detection="High" RPN="27">
      <failurecause name="Read 3D Position_MessageRecv"/>
    </failuremode>
    <failuremode name="Error reading 3D position"
      FailureLocalEffect="No signal" SystemFailureLevelEffect="No response"
      severity="VeryHigh" occurrence="Remote" detection="Low" RPN="48">
      <failurecause name="Read 3D Position_Message0Recv"/>
    </failuremode>
    <failuremode name="" FailureLocalEffect=""
      SystemFailureLevelEffect="" severity="None" occurrence="Remote"
      detection="AlmostCertain" RPN="1">
      <failurecause name="Read 3D Position_Message1Recv"/>
    </failuremode>
  </component>
  <component name="3D Sensor">
    <failuremode name="wrong Movement of 3D"
      FailureLocalEffect="error in calculation 
      SystemFailureLevelEffect="incorrect response" severity="None"
      occurrence="Remote" detection="AlmostCertain" RPN="1">
      <failurecause name="Move 3D sensor on Patient Body_MessageRecv"/>
    </failuremode>
  </component>
</xml:xmi>
<failuremode name="" FailureLocalEffect="" SystemFailureLevelEffect="" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Localize_MessageRecv"/>
</failuremode>

<failuremode name="Wrong 3D movement" FailureLocalEffect="Wrong calculation" SystemFailureLevelEffect="System crash" severity="Low" occurrence="High" detection="AlmostCertain" RPN="35">
  <failurecause name="Move 3D Sensor on patient Body_MessageRecv"/>
</failuremode>

<failuremode name="No Position signal" FailureLocalEffect="No effect" SystemFailureLevelEffect="None" severity="None" occurrence="Remote" detection="VeryLow" RPN="7">
  <failurecause name="Localize_Message0Recv"/>
</failuremode>

<failuremode name="Wrong 3D movement" FailureLocalEffect="incorrect response" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="Low" RPN="6">
  <failurecause name="Move 3D Sensor on patient Body_Message0Recv"/>
</failuremode>

</component>

<component name="HMI"/>

<component name="Operator">
  <failuremode name="Wrong representation of the patient" FailureLocalEffect="Wrong interpretation by the operator" SystemFailureLevelEffect="Wrong output with incorrect moves" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="3D representation Of Patient_MessageRecv"/>
  </failuremode>

  <failuremode name="Bad 3D sensor manipulation" FailureLocalEffect="Bad Patient Model" SystemFailureLevelEffect="Pressure on the Patient too high" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Bad Indication_MessageRecv"/>
  </failuremode>

</component>

<component name="HMI">
  <failuremode name="Wrong Signal" FailureLocalEffect="Incorrect calibration response" SystemFailureLevelEffect="Wrong output" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Start Calibrate patient Model_MessageRecv"/>
  </failuremode>

  <failuremode name="Invissible Patient Model" FailureLocalEffect="Lost of signals" SystemFailureLevelEffect="No response" severity="VeryHigh" occurrence="Remote" detection="Moderate" RPN="8">
    <failurecause name="Invissible Patient Model"/>
  </failuremode>

</component>
<failurecause name="Show Patient Model_MessageRecv"/>
</failuremode>

<failuremode name="Wrong input" FailureLocalEffect="Invalid update" SystemFailureLevelEffect="Wrong output" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Validate_MessageRecv"/>
</failuremode>

<failuremode name="Wrong input" FailureLocalEffect="Invalid update" SystemFailureLevelEffect="Wrong output" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Validate_MessageRecv"/>
</failuremode>

<failuremode name="Wrong input" FailureLocalEffect="Invalid update" SystemFailureLevelEffect="Wrong output" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Validate_MessageRecv"/>
</failuremode>

<failuremode name="Wrong input" FailureLocalEffect="Invalid update" SystemFailureLevelEffect="Wrong output" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Validate_MessageRecv"/>
</failuremode>

<failurecause name="HMI alternative failure cause_MessageRecv"/>
</failuremode>
</component>

<component name="Motion Planner">
  <failuremode name="Failed Motion Planner " FailureLocalEffect="No response" SystemFailureLevelEffect="System hangs" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Motion Planner failure cause_MessageRecv"/>
  </failuremode>
</component>

<component name="TELEOP Controller">
  <failuremode name="Wrong Control signal" FailureLocalEffect="Wrong signal " SystemFailureLevelEffect="Wrong output" severity="Low" occurrence="Low" detection="AlmostCertain" RPN="15">
    <failurecause name="Control in a position_MessageRecv"/>
  </failuremode>

  <failuremode name="Lost of control" FailureLocalEffect="High" SystemFailureLevelEffect="Low" severity="Moderate" occurrence="Remote" detection="High" RPN="18">
    <failurecause name="Control in a position_Message0Recv"/>
  </failuremode>
</component>

<component name="Geometrical model">
  <failuremode name="Wrong Calculation" FailureLocalEffect="High" SystemFailureLevelEffect="Low" severity="VeryHigh" occurrence="Remote" detection="VeryRemote" RPN="72">
    <failurecause name="6:Calculate_Message_MessageRecv"/>
  </failuremode>

  <failuremode name="Failed length Calculation" FailureLocalEffect="High" SystemFailureLevelEffect="None" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="calculate length_MessageRecv"/>
  </failuremode>
</component>

<component name="Position Controller">
  <failuremode name="Lost of signal regulation " FailureLocalEffect="Severe effect" SystemFailureLevelEffect="High"
<failuremode name="Regulate_MessageRecv"/>
</failuremode>

<failuremode name="Lost of signal regulation 
FailureLocalEffect="Very high 
SystemFailureLevelEffect="High
severity="Low" occurrence="Moderate" detection="Moderate" RPN="20">
<failurecause name="Regulate_Message0Recv"/>
</failuremode>

<failuremode name="Lost of signal regulation 
FailureLocalEffect="Extremely 
SystemFailureLevelEffect="High
severity="None" occurrence="Remote" detection="AlmostCertain" 
RPN="1">
<failurecause name="Regulate_Message1Recv"/>
</failuremode>

<component name="Robot Model">
<failuremode name="failed signal to read" 
FailureLocalEffect="Low" SystemFailureLevelEffect="None
severity="Low" occurrence="Remote" detection="AlmostCertain" 
RPN="5">
<failurecause name="Read_MessageRecv"/>
</failuremode>

<component name="Patient Model">
<failuremode name="Wrong Number Points" 
FailureLocalEffect="Affects HMI 
SystemFailureLevelEffect="Affects system smooth running" severity="Moderate" occurrence="Remote" 
detection="AlmostCertain" RPN="6">
<failurecause name="Create (Number of Points)_MessageRecv"/>

<failuremode name="wrong calculation 
FailureLocalEffect="wrong signal to the other components"
SystemFailureLevelEffect="wrong output" severity="HazardWithWarning" occurrence="AlmostCertain" detection="AlmostCertain" RPN="90">
<failurecause name="Calculate Model_MessageRecv"/>
</failuremode>

<failuremode name="Read wrong signal" 
FailureLocalEffect="Wrong input" SystemFailureLevelEffect="Wrong response" severity="None" occurrence="Remote" 
detection="AlmostCertain" RPN="1">
<failurecause name="Read_Message0Recv"/>
</failuremode>
</component>
</System>
Appendix B

B.1 Test Case 1: XML Target Model

```xml
<?xml version="1.0" encoding="ASCII"?>
<System xmi:version="2.0"
xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of model">
    <component name="Component1">
        <failuremode name="Component1 Failure mode"
            FailureLocalEffect="Affect component 2"
            SystemFailureLevelEffect="shutdown the system" severity="Low"
            occurrence="BeyondModerate" detection="High" RPN="75">
            <failurecause name="Com from Comp2to1_MessageRecv"/>
        </failuremode>
    </component>
    <component name="Component2">
        <failuremode name="Component2 Failure mode"
            FailureLocalEffect="Affects Component 1"
            SystemFailureLevelEffect="No effect on the system" severity="Very Minor"
            occurrence="Very Low" detection="AlmostCertain" RPN="1">
            <failurecause name="Com from Comp1to2_MessageRecv"/>
        </failuremode>
    </component>
</System>
```

B.2 Test Case 2: XML Target Model

```xml
<?xml version="1.0" encoding="ASCII"?>
<System xmi:version="2.0"
xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of model">
    <component name="Component1">
        <failuremode name="failure mode2"
            FailureLocalEffect="No effect"
            SystemFailureLevelEffect="None" severity="None"
            occurrence="Remote" detection="AlmostCertain" RPN="1">
            <failurecause name="Message0Recv"/>
        </failuremode>
        <failuremode name="failure mode4"
            FailureLocalEffect="Low Effect on Component2" severity="Very Minor"
            SystemFailureLevelEffect="Low Effect"
            occurrence="Very Low" detection="AlmostCertain" RPN="4">
            <failurecause name="Message2Recv"/>
        </failuremode>
    </component>
    <component name="Component2">
        <failuremode name="failure mode1"
            FailureLocalEffect="Stop Component1"
            SystemFailureLevelEffect="Affects the system" severity="High"
            occurrence="Moderate" detection="AlmostCertain" RPN="28">
            <failurecause name="MessageRecv"/>
        </failuremode>
    </component>
</System>
```
B.3 Test Case3: XML Target Model

```xml
<?xml version="1.0" encoding="ASCII"?>
<System xmi:version="2.0" xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of Test case3 model">
  <component name="Component1">
    <failuremode name="Failure Mode 3" FailureLocalEffect="Affects component 2" SystemFailureLevelEffect="Low effect" severity="None" occurrence="High" detection="Moderately High" RPN="35">
      <failurecause name="Message1 from Comp1to2_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 4" FailureLocalEffect="Moderate effect on other component" SystemFailureLevelEffect="Affect the system" severity="Moderate" occurrence="Beyond Moderate" detection="AlmostCertain" RPN="30">
      <failurecause name="Message4 from Comp1to2_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 6" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Moderate effect on the system" severity="VeryLow" occurrence="Remote" detection="Low" RPN="24">
      <failurecause name="Message6 from Comp3to2_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Component2">
    <failuremode name="Failure Mode 1" FailureLocalEffect="Low effect on other component" SystemFailureLevelEffect="Affect the system" severity="None" occurrence="High" detection="Moderate" RPN="35">
      <failurecause name="Message1 from Comp1to2_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 5" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Shut down the system" severity="HazardWithWarning" occurrence="Moderate" detection="AlmostCertain" RPN="36">
      <failurecause name="Message5 from Comp2to3_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Component3">
    <failuremode name="Failure Mode 2" FailureLocalEffect="Affect component 1" SystemFailureLevelEffect="Low" severity="None" occurrence="ModeratelyHigh" detection="AlmostCertain" RPN="6">
      <failurecause name="Message2 from Comp2to3_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 5" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Shut down the system" severity="HazardWithWarning" occurrence="Moderate" detection="AlmostCertain" RPN="36">
      <failurecause name="Message5 from Comp2to3_MessageRecv"/>
    </failuremode>
  </component>
</System>
```
<failurecause name="Message5 from Comp2to3_MessageRecv"/>
</failuremode>
</component>
</System>

B.4 Test Case4: XML Target Model

<?xml version="1.0" encoding="ASCII"?>
<System xmlns:xmi="http://www.omg.org/XMI" xmlns=FMEA="name="FMEA of model">
  <component name="Component5">
    <failuremode name="Failure Mode 3" FailureLocalEffect="None"
                 SystemFailureLevelEffect="None" severity="None"
                 occurrence="Remote" detection="AlmostCertain"
                 RPN="1">      
      <failurecause name="Message13 From Com4to5_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 6" FailureLocalEffect="No effect"
                 SystemFailureLevelEffect="None" severity="None"
                 occurrence="Remote" detection="AlmostCertain"
                 RPN="1">      
      <failurecause name="Message17 From Com4to5 in CombFrag_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Component4">
    <failuremode name="Failure Mode 2" FailureLocalEffect="Affects Component 4"
                 SystemFailureLevelEffect="None" severity="None"
                 occurrence="Low" detection="AlmostCertain"
                 RPN="3">      
      <failurecause name="Message12 From Com2to4_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 6" FailureLocalEffect="None"
                 SystemFailureLevelEffect="None" severity="None"
                 occurrence="Remote" detection="AlmostCertain"
                 RPN="1">      
      <failurecause name="Message16 From Com2to4 in CombFrag_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Component1">
    <failuremode name="Failure Mode 8" FailureLocalEffect="Low effect on other component"
                 SystemFailureLevelEffect="Low" severity="High"
                 occurrence="Remote" detection="Very High"
                 RPN="14">      
      <failurecause name="Message2 from Comp2to1_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 11" FailureLocalEffect="Low effect on other component"
                 SystemFailureLevelEffect="No visible effect" severity="None"
                 occurrence="Remote" detection="AlmostCertain"
                 RPN="1">      
      <failurecause name="Message5 from Comp2to1 in comFrag_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 4" FailureLocalEffect="Affects Component 5"
                 SystemFailureLevelEffect="No effect" severity="None"
                 occurrence="Remote" detection="AlmostCertain"
                 RPN="1">      
      <failurecause name="Message5 from Comp2to3_MessageRecv"/>
    </failuremode>
  </component>
</System>
<failurecause name="Message14 From Com5to1 in CombFrag_MessageRecv"/>
</failuremode>
</component>

<component name="Component2">

<failuremode name=" Failure Mode 7"
FailureLocalEffect="Low effect" SystemFailureLevelEffect="Low effect" severity="None" occurrence="Low" detection="Low" RPN="18">

<failurecause name="Message1 From Comp1to2_MessageRecv"/>
</failuremode>

<failuremode name=" Failure Mode 10" FailureLocalEffect="High" SystemFailureLevelEffect="High effect" severity="High" occurrence="BeyondModerate" detection="AlmostCertain" RPN="35">

<failurecause name="Message4 from Comp3to2 in comFrag_MessageRecv"/>
</failuremode>

<failuremode name=" Failure Mode 1" FailureLocalEffect="Affect Component1" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">

<failurecause name="Message11 from Comp1 to 2_MessageRecv"/>
</failuremode>

</component>

<component name="Component3">

<failuremode name=" Failure Mode 9" FailureLocalEffect="Low effect on other component" SystemFailureLevelEffect="Very low effect" severity="None" occurrence="ModeratelyHigh" detection="AlmostCertain" RPN="6">

<failurecause name="Message3 from Comp1to3 in comFrag_MessageRecv"/>
</failuremode>

<failuremode name=" Failure Mode 5" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Affect the system" severity="None" occurrence="Moderate" detection="Low" RPN="24">

<failurecause name="Message15 From Com1to3 in CombFrag_MessageRecv"/>
</failuremode>

</component>

</System>

B.5 Test Case5: XML Target Model

<?xml version="1.0" encoding="ASCII"?>
<System xmlns:xmi="http://www.omg.org/XMI" xmlns="FMEA" name="FMEA of test case5">

<component name="Component1">

<failuremode name="CS Failure Mode 2"
FailureLocalEffect="Affects Componet 2" SystemFailureLevelEffect="None" severity="None" occurrence="High" detection="AlmostCertain" RPN="7">

<failurecause name="InformationItem3 from Comp2to1"/>
</failuremode>

</component>

</System>
<failuremode name="CS Failure Mode 5" FailureLocalEffect="Affect component 3" SystemFailureLevelEffect="None" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="InformationItem5 from Comp3to1"/>
</failuremode>

<failuremode name="Failure Mode 3" FailureLocalEffect="Affect component 3" SystemFailureLevelEffect="Low effect on the system" severity="None" occurrence="VeryHigh" detection="AlmostCertain" RPN="8">
  <failurecause name="Message3 from Comp3to1_MessageRecv"/>
</failuremode>

</component>

<component name="Component2">
  <failuremode name="CS Failure Mode 1" FailureLocalEffect="Low effect on others" SystemFailureLevelEffect="Moderate effect on the system" severity="None" occurrence="Low" detection="VeryLow" RPN="21">
    <failurecause name="InformationItem1 from Comp1to2"/>
  </failuremode>

  <failuremode name="CS Failure Mode 4" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Low effect on the system" severity="Low" occurrence="Remote" detection="High" RPN="15">
    <failurecause name="InformationItem6 from Comp3to2"/>
  </failuremode>

  <failuremode name="Failure Mode 1" FailureLocalEffect="Low effect on others component" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Message1 from Class1to2_MessageRecv"/>
  </failuremode>

  <failuremode name="Failure Mode 5" FailureLocalEffect="Minor effect" SystemFailureLevelEffect="Moderate effect" severity="VeryLow" occurrence="Remote" detection="Low" RPN="24">
    <failurecause name="Message5 from Comp3to2_MessageRecv"/>
  </failuremode>

</component>

<component name="Component3">
  <failuremode name="CS Failure Mode 5" FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Low Effect" severity="VeryHigh" occurrence="Remote" detection="AlmostCertain" RPN="8">
    <failurecause name="InformationItem2 from Comp1to3"/>
  </failuremode>

  <failuremode name="CS Failure Mode 3" FailureLocalEffect="Affects Others" SystemFailureLevelEffect="High effect on the system" severity="Low" occurrence="High" detection="AlmostCertain" RPN="35">
    <failurecause name="InformationItem4 from Comp2to3"/>
  </failuremode>

  <failuremode name="Failure Mode 2" FailureLocalEffect="Low effect" SystemFailureLevelEffect="None" severity="None" occurrence="Remote" detection="Moderate" RPN="5">
    <failurecause name="Message2 from Comp2to3_MessageRecv"/>
  </failuremode>

</failuremode>
<failuremode name="Failure Mode 4" FailureLocalEffect="None" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Message4 from Comp1to3_MessageRecv"/>
</failuremode>
</component>
</System>

B.6 Test Case6: XML Target Model

<?xml version="1.0" encoding="ASCII"?>
<System xmi:version="2.0" xmlns:xmi="http://www.omg.org/XMI" xmlns:FMEA="name="FMEA of model">
  <component name="Component1">
    <failuremode name="Failure Mode 1 of Component 1" FailureLocalEffect="Affects Component 2" SystemFailureLevelEffect="No effect" severity="Low" occurrence="Remote" detection="AlmostCertain" RPN="5">
      <failurecause name="Info to Component 1"/>
    </failuremode>
    <failuremode name="Failure Mode 2 of Component 1" FailureLocalEffect="None" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
      <failurecause name="Message3 from Comp3to1_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 3 of Component 1" FailureLocalEffect="Affect the next component" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="Remote" RPN="8">
      <failurecause name="Message6 from Comp2to1_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 4 of Component 1" FailureLocalEffect="Affect component 3" SystemFailureLevelEffect="Low effect on the system" severity="Low" occurrence="Remote" detection="Remote" RPN="40">
      <failurecause name="Message8 from Com3to1_MessageRecv"/>
    </failuremode>
    <failuremode name="Failure Mode 5 of Component 1" FailureLocalEffect="Affects Component 2" SystemFailureLevelEffect="Low effect" severity="None" occurrence="Beyond Moderate" detection="AlmostCertain" RPN="5">
      <failurecause name="Message16 from Comp2to1_MessageRecv"/>
    </failuremode>
  </component>
  <component name="Component2">
    <failuremode name="Failure Mode 1 of Component 2" FailureLocalEffect="Affect other component"
SystemFailureLevelEffect="High" severity="VeryLow"
occurrence="ExtremelyHigh" detection="Low" RPN="216">
  <failurecause name="Info from comp1to2"/>
</failuremode>

<failuremode name="Failure Mode 2 of Component 2"
FailureLocalEffect="Affect one component"
SystemFailureLevelEffect="None" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
  <failurecause name="Info from Comp5to2"/>
</failuremode>

<failuremode name="Failure Mode 3 of Component 2"
FailureLocalEffect="No effect" SystemFailureLevelEffect="None"
severity="None" occurrence="Remote" detection="Moderate" RPN="5">
  <failurecause name="Message1 from Comp1to2_MessageRecv"/>
</failuremode>

<failuremode name="Failure Mode 4 of Component 2"
FailureLocalEffect="Low effect" SystemFailureLevelEffect="No effect"
severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Message5 from Comp3to2_MessageRecv"/>
</failuremode>

<failuremode name="Failure Mode 5 of Component 2"
FailureLocalEffect="Affect other component" SystemFailureLevelEffect="Affect the system"
severity="None" occurrence="ExtremelyHigh" detection="Low" RPN="54">
  <failurecause name="Message11 from Comp1to2_MessageRecv"/>
</failuremode>

<failuremode name="Failure Mode 6 of Component 2"
FailureLocalEffect="Affect others" SystemFailureLevelEffect="No effect"
severity="None" occurrence="VeryHigh" detection="Moderate" RPN="40">
  <failurecause name="Info from Comp4to3"/>
</failuremode>

<failuremode name="Failure Mode 7 of Component 2"
FailureLocalEffect="Affect Component 2" SystemFailureLevelEffect="None"
severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Message2 from Comp2to3_MessageRecv"/>
</failuremode>

<component name="Component3">
  <failuremode name="Failure Mode 1 of Component 3"
FailureLocalEffect="No effect" SystemFailureLevelEffect="Low Effect"
severity="Low" occurrence="Beyond Moderate" detection="Almost Certain" RPN="25">
    <failurecause name="Info from Comp1to3"/>
  </failuremode>

  <failuremode name="Failure Mode 2 of Component 3"
FailureLocalEffect="Affects others" SystemFailureLevelEffect="No Effect"
severity="None" occurrence="VeryHigh" detection="Moderate" RPN="40">
    <failurecause name="Info from Comp4to3"/>
  </failuremode>

  <failuremode name="Failure Mode 3 of Component 3"
FailureLocalEffect="Affect Component 2" SystemFailureLevelEffect="None"
severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    <failurecause name="Message2 from Comp2to3_MessageRecv"/>
  </failuremode>
</component>
<failuremode name="Failure Mode 4 of Component 3"
FailureLocalEffect="Affect other components"
SystemFailureLevelEffect="No effect on the system" severity="High"
occurrence="Remote" detection="AlmostCertain" RPN="7">
  <failurecause name="Message4 from Comp1to3_MessageRecv"/>
</failuremode>

<failuremode name="Failure Mode 5 of Component 3"
FailureLocalEffect="Affect component 2" SystemFailureLevelEffect="No effect on the system" severity="None"
occurrence="Remote" detection="AlmostCertain" RPN="1">
  <failurecause name="Message7 from Comp1to3_MessageRecv"/>
</failuremode>

<failuremode name="Failure Mode 6 of Component 3"
FailureLocalEffect="Affect component 5 effect"
SystemFailureLevelEffect="None" severity="None" occurrence="Remote"
detection="AlmostCertain" RPN="1">
  <failurecause name="Message13 from Comp5to3_MessageRecv"/>
</failuremode>

</component>

<component name="Component4">
  <failuremode name="Failure Mode 2 of Component 4"
FailureLocalEffect="None" SystemFailureLevelEffect="No effect"
severity="None" occurrence="Remote" detection="AlmostCertain"
RPN="1">
    <failurecause name="Info from Comp1to4"/>
  </failuremode>

  <failuremode name="Failure Mode 1 of Component 4"
FailureLocalEffect="High effect" SystemFailureLevelEffect="None"
severity="None" occurrence="Remote" detection="AlmostCertain"
RPN="1">
    <failurecause name="Info from Comp2to4"/>
  </failuremode>

  <failuremode name="Failure Mode 4 of Component 4"
FailureLocalEffect="Low effect" SystemFailureLevelEffect="No effect on the system"
severity="High" occurrence="Remote" detection="High"
RPN="21">
    <failurecause name="Info from Comp5to4"/>
  </failuremode>

  <failuremode name="Failure Mode 3 of Component 4"
FailureLocalEffect="No effect" SystemFailureLevelEffect="None"
severity="None" occurrence="Remote" detection="AlmostCertain"
RPN="1">
    <failurecause name="Info from Comp3to4"/>
  </failuremode>

  <failuremode name="Failure Mode 5 of Component 4"
FailureLocalEffect="None" SystemFailureLevelEffect="No effect"
severity="None" occurrence="High" detection="AlmostCertain" RPN="7">
    <failurecause name="Message4 from Comp3to4_MessageRecv"/>
  </failuremode>
</component>

<component name="Component5">
  <failuremode name="Failure Mode 4 of Component 5"
FailureLocalEffect="Affects others" SystemFailureLevelEffect="Affect the system"
severity="VeryHigh" occurrence="High" detection="AlmostCertain" RPN="56">
  
  <failurecause name="Info from Comp1to5"/>
  </failuremode>

  <failuremode name="Failure Mode1 of Component 5"
FailureLocalEffect="None" SystemFailureLevelEffect="Moderate effect" severity="None" occurrence="High" detection="Very Low" RPN="49">
    
    <failurecause name="Info from Comp4to5"/>
  </failuremode>

  <failuremode name="Failure Mode2 of Component 5"
FailureLocalEffect="None" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    
    <failurecause name="Info from Comp2to5"/>
  </failuremode>

  <failuremode name="Failure Mode3 of Component 5"
FailureLocalEffect="None" SystemFailureLevelEffect="No effect" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    
    <failurecause name="Info from Comp3to5"/>
  </failuremode>

  <failuremode name="Failure Mode5 of Component 5"
FailureLocalEffect="Affects Component 2" SystemFailureLevelEffect="Affect the System" severity="Minor" occurrence="Remote" detection="VeryLow" RPN="21">
    
    <failurecause name="Message12 from Comp2to5_MessageRecv"/>
  </failuremode>

  <failuremode name="Failure Mode6 of Component 5"
FailureLocalEffect="No effect" SystemFailureLevelEffect="None" severity="None" occurrence="Remote" detection="AlmostCertain" RPN="1">
    
    <failurecause name="Message14 from Comp4to5_MessageRecv"/>
  </failuremode>
</component>
</System>
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