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Automating ISO 26262 Hardware Evaluation Methodologies

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Abstract

The constant evolution of vehicles, incorporating more commodities and functionalities, has been made possible by electric, electronic and programmable electronic components. To assure the reliability of the safety-related systems that use those components, functional safety standards are created to define processes and guidelines for their development. Some of those systems control important functions such as steering and braking in road vehicles. For that purpose, the Automotive Functional Safety Standard, ISO 26262, was launched.

Manual Safety Analysis for complex electronic systems can be a difficult and time-demanding task, with no assurance of success, as it is error prone. With that in mind, the University of Hull developed a safety and reliability tool, to automate some of the safety analysis steps. Hierarchically-Performed Hazard Origin and Propagation Studies (HiP-HOPS) is that state-of-the-art tool.

For the development of hardware systems, ISO 26262 proposes a set of evaluation metrics, which can be used to compare system's designs. Furthermore, it guides the designer through the process of choosing safety mechanisms to assure the targets for those metrics are achieved. Currently, the safety analysis that is being done using HiP-HOPS does not consider those safety mechanisms. It also does not perform the metrics calculation.

The aim of this thesis is to extend HiP-HOPS capabilities, so it can incorporate those safety mechanisms and perform metrics calculations automatically, to allow the user to test different hardware implementations and point to the best solution.

The topics here stated, namely safety analysis, HiP-HOPS and the standard ISO 26262, are explored in the firstly looked at Literature Review. Then, the changes made to HiP-HOPS are explained and validated through the analysis of a chosen hardware system. The last part is dedicated to result analysis, final considerations and further developments on the metrics software program.

Resumo

A evolução constante dos veículos, incorporando mais comodidades e funcionalidades, tem sido possível graças a componentes elétricos, eletrónicos e de eletrónica programável. De modo a assegurar a fiabilidade de sistemas relacionados com segurança que usam esses componentes, normas de segurança funcional têm sido criadas para definir processos e metodologias para o seu desenvolvimento. Alguns desses sistemas controlam funções importantes como direção e travagem em automóveis. Para esse propósito, a norma de segurança funcional automóvel, ISO 26262, foi lançada.

Realizar análise de segurança manualmente, em sistemas eletrónicos complexos, pode ser uma tarefa difícil e demorada, sem garantia de sucesso, visto que é suscetível ao erro humano. Com esta problemática em mente, a *University of Hull* desenvolveu uma ferramenta de segurança e fiabilidade, para automatizar algumas das etapas da análise de segurança. Essa ferramenta designa-se por *Hierarchically-Performed Hazard Origin and Propagation Studies* (HiP-HOPS).

Para o desenvolvimento de sistemas de *hardware*, a norma ISO 26262 propõe um conjunto de métricas de avaliação que são utilizadas para comparar diferentes implementações. Além disso, guia o utilizador ao longo de um processo de escolha de mecanismos de segurança que permitem assegurar o cumprimento dos objetivos quantitativos das métricas. Neste momento, a análise de segurança feita através do HiP-HOPS não tem em consideração esses mecanismos de segurança, nem faz o cálculo das métricas.

O objetivo desta tese é extender as capacidades do HiP-HOPS, de modo a incorporar os mecanismos de segurança na sua análise e fazer o cálculo das métricas automaticamente, de forma a permitir que o utilizador teste implementações de *hardware* diferentes e apontá-lo na direção da melhor solução.

Os tópicos aqui mencionados, nomeadamente análise de segurança, a ferramenta HiP-HOPS e a norma ISO 26262, serão explorados na revisão de literatura. Seguidamente, as mudanças feitas no HiP-HOPS serão explicadas e validadas através da análise do sistema de *hardware* escolhido. A última parte será dedicada à análise dos resultados obtidos, às considerações finais e a futuros desenvolvimentos do *software* para as métricas.

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This thesis is dedicated to all of you,

João Tavares

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Symbols and Abbreviations

List of Abbreviations

HiP-HOPS - Hierarchically-Performed Hazard Origin and Propagation Studies
FMEA - Failure Modes and Effects Analysis
FTA – Fault Tree Analysis
SILs - Safety Integrity Levels
PMHF - Probabilistic metric for Random Hardware Failures
PLD – Programmable Logical Device
FPGA – Field Programmable Gate Array
ECU – Electronic Control Unit
E/E/EP – Electric and/or Electronic and/or Programmable Electronic system
CENELEC – European Committee for Electrotechnical Standardization
ISO – International Organization for Standardization
IEC – International Electrotechnical Commission
FPTC - Fault Propagation and Transformation Calculus
SEFT - State-Event Fault Tree
CFT - Component Fault Tree
CSA - Compositional Safety Analysis
DSPN - Deterministic Stochastic Petri Net
NSGA - Non-Dominated Sorting Genetic Algorithm
ADC – Analog-to-Digital Converter
LED - Light-Emitting Diode
HW – Hardware
XML – eXtensible Markup Language

Chapter 1

Introduction

This initial chapter describes the work presented in this document. It begins with the motivation of the thesis, then the aim of the project and the different steps required to achieve it and finally, the organization of the document.

1.1. Problem

As engineering systems get more complex, new and more elaborate system failure modes are introduced due to systematic and random hardware failures. Classic manual safety and reliability analysis techniques become more difficult and error prone due to that complexity. To solve this problem, computerized tools which simplify the analysis process, need to be developed. One of those tools is called HiP-HOPS (Hierarchically-Performed Hazard Origin and Propagation Studies) and is capable of automating the synthesis and analysis of Fault Trees and FMEAs (Failure Modes and Effects Analyses). It only requires the initial component failure data to be provided, which can be reused. Furthermore, it is possible to use HiP-HOPS to optimize system models, reliability vs. cost. In this case, genetic algorithms are used to evolve initial non-optimal systems.

Some of the most complex electric/electronic systems nowadays are inside of our most common vehicles, which can contain dozens or even hundreds of ECUs. To combat the automotive industry's critical need to protect these systems, a standard has been launched in 2011. The standard ISO 26262, is an adaptation of the universal safety standard IEC 61508 for road vehicles and contains indications for the development of security systems with E/E/EP components. Currently there is little guidance and tool support regarding the standard and its hardware evaluation metrics, so it is sensible choice to incorporate the procedures of the standard, extending HiP-HOPS capabilities and providing the Automotive Industry with an even more interesting tool.

1.2. Thesis' Aim

The aim of this Thesis is to propose ways to change the HiP-HOPS to better support the hardware architecture verification procedures of ISO 26262.

Firstly, there is the need to understand how the most used manual safety analysis techniques, FTA and FMEA, work has they are used by HiP-HOPS.

In the following stage, the HiP-HOPS methodology must be explored. HiP-HOPS uses a failure model, which is different from the functional one.

The next step will be to study ISO 26262, especially Part 5 - Product development at the hardware level, to understand how ISO 26262 hardware architecture verification procedures work, and then figure out how it is possible to include these procedures in HiP-HOPS.

To validate the verification procedures a model will be necessary, so a simple electronic system will be chosen, the failure model of that system will be designed and the failure behavior information of its components inserted.

Finally, a program will be made to apply the evaluation metrics to the model and safety mechanisms will be incorporated in HiP-HOPS. These are components or procedures implemented to prevent safety goal violation.

The required major tasks to be performed during this dissertation are the following:

- Establishment of the differences between FTA in HiP-HOPS and FTA in ISO 26262;
- Establishment of how to map Safety Mechanisms in FTA;
- Analysis of ISO 26262 hardware evaluation techniques;
- Development of a failure model for a simple electronic system;
- Establishment of the failure behavior of the model and its components;
- Creation of a fault tree, manually, to verify if the hardware evaluation techniques work;
- Development of a program or/and functions in HiP-HOPS that reads information from the model and applies the hardware evaluation techniques;

1.3. Document Outline

The structure of this document is as follows:

- In the current chapter the content of this document and motivation of the project are introduced.
- Chapter 2 is devoted to the Literature Review: Functional Safety and brief introduction to SILs, safety and reliability analysis techniques, introduction to HiP-HOPS and overview of the ISO 26262 standard.
- Chapter 3 will focus on ISO 26262 part 5- Product development at the hardware level, specifically in what are considered safety mechanisms and how the hardware architectural evaluation techniques are implemented. Then, there will be the proposition of methods to implement these concepts in HiP-HOPS.
- In Chapter 4, the HiP-HOPS changes will be explained and the concepts found in ISO 26262 part 5, analyzed in chapter 3 and implemented in HiP-HOPS will be validated through a case study.
- Chapter 5 is the general review of what has been achieved and the final conclusions reached.

Chapter 2

Literature and Concepts review

This Chapter is to review the thesis main concepts. Safety Analysis is introduced and the concept of SILs introduced. The main techniques to perform Safety Analysis are exposed with special emphasis to FTA. The state-of-the-art safety tool, HiP-HOPS methodology is explored and its capabilities reviewed and, finally, the safety standard ISO 26262 is briefly introduced.

2.1. Functional Safety and SILs

Functional Safety standards aid system designers with guidelines for the development of E/E/EP systems with the ability to perform safety functions. SILs are used to allocate safety requirements to the system's components in order to prevent unacceptable risk. This section clarifies what is safety and Functional Safety and introduces the SILs concept.

2.1.1. Safety, Functional Safety and other important concepts

According to safety standards such as IEC 61508, and CENELEC safety is defined as: "freedom from unacceptable risk of physical injury or of damage to the health of people, either directly or indirectly as a result of damage to property or to environment".

Functional Safety is defined as: "absence of unreasonable risk due to hazards caused by malfunction behavior of E/E/EP systems" [1].

Other important concepts connected to Functional Safety are presented below [1]:

- Harm: "Physical injury or damage to the health of persons";
- Hazard: "A potential source of Harm";
- Risk: "Risk can be described as a function of a frequency of occurrence of hazardous events, the ability to avoid specific harm or damage through timely reactions of the persons involved (controllability) and the potential severity of the resulting harm or damage";
- Residual Risk: "Risk remaining after protective measures have been taken";
- Unreasonable Risk: "Risk judged to be unacceptable in a certain context, according to valid societal moral concepts";

- Failure: “Termination of the ability of an element to perform a function as required”;
- Failure Mode: “Manner in which an element or an item fails”;
- Systematic Failure: “Failure related in a deterministic way to a certain cause, that can only be eliminated by a change of the design or of the manufacturing process, operational procedures, documentation or other relevant factors”;
- Random Hardware Failure: “Failure that can occur unpredictably during the lifetime of a hardware element and that follows a probability distribution”;
- Safety-Related Systems: “Systems that perform a function or functions that ensure that risks are kept at an acceptable level”;
- Safety Integrity: “The probability of a safety-related system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time”;
- Safety Goal: “Top-level safety requirement as a result of the hazard analysis and risk assessment”;
- Safety Measure: “Activity or technical solution to avoid or control Systematic Failures and to detect Random Hardware Failures or control Random Hardware Failures or mitigated their harmful effects”;

2.1.2. Functional Safety Standards

The international standard of Functional Safety, applicable to all industries, is IEC 61508, entitled “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related systems”. It provides requirements and guidelines that enable the development of safety-related systems with a safe framework.

However, the need for different standards, applicable to specific industries, led to the creation of different IEC 61508 branches. Examples of these adaptations are present bellow:

- ISO 26262 – Automotive Industry;
- EN 5012X – Railway Industry;
- IEC 61511 – Process Industry.

This thesis is intended to use the concepts in the ISO 26262 – “Road Vehicles – Functional Safety” adaptation, since it is a recent standard (2011) and there is little guidance and tool support.

2.1.3. SILs

Safety-related systems are used to make sure that risks are on an acceptable level. The E/E/EP systems in which they are applied have Safety Goals and Safety Requirements, that state which is that acceptable level of risk.

Safety requirements are derived through a process which uses functional hazard assessment and risk analysis techniques. This process aims to determine: (1) critical system functions, (2) safety requirements for hazards that cannot be avoided, related to those functions and (3) demands for additional safety functions, to achieve acceptable levels of risk.

Safety Integrity Levels (SILs) are classification levels used in safety-critical systems. They were developed in the UK as Safety Health & Safety guidelines and adopted by IEC 61508 and other standards. Five levels of SILs are used: SIL0 (no additional safety requirements) to SIL4 (high safety requirements demand). In SIL decomposition, architectural elements are assigned lower or equal SILs, which combined should fulfil the SIL of their parent functions. This is a manual and time demanding process and as networked architectures get more complex, with multiple safety functions, an automated solution is needed to keep up with the increased difficulty.

SILs are used to allocate functional safety requirements to a system and give requirements for the implementation of critical functions. A function with lower required failure probability has to have a higher SIL. The distribution of the integrity levels in subsystem components can be arranged in different ways. For example in a subsystem with SIL four, the components can have three level two SIL or a single level four SIL. Elimination of common cause failure is required when fault tolerant architectures are employed to achieve the required SIL. Evidence must be given that the software and hardware elements of each function meet their allocated SILs. The Standards specify that failure rate prediction to assess if SILs have been met is only possible in random hardware failures. The techniques used are probabilistic assessment using failure rates and reliability prediction models (FMEA, FTA, and Markov). Standards also consider the systematic faults in software and hardware introduced by humans in specification, design, manufacturing and installation, although these faults cannot be quantified.

That said, this section describing SILs is merely introductory, as it is important for safety analysis. Although, it does not have a big relevance for this thesis.

2.2. ISO 26262

This section is to introduce the recent Functional Safety Standard for the automotive industry, ISO 26262. Automotive SILs (ASILs) will also be mentioned. The thesis focuses on this Standard.

2.2.1. ISO 26262 Introduction

It is the adaptation of IEC 61508 to electric, electronic and software systems for road vehicles. Safety is extremely important in automotive development. Such functions as driver assistance, propulsion, vehicle dynamic control and passive/active safety systems are in further development. The need for safe system development processes and the ability to verify if the system safety objectives are satisfied is increasingly important.

ISO 26262 consists of the following parts, under the general title Road vehicles – Functional safety [1]:

- Part 1: Vocabulary – terms and definitions used throughout the standard;
- Part 2: Management of functional safety – specifies requirements for the management of functional safety for automotive applications;
- Part 3: Concept phase – specifies requirements for risk analysis and assessment and for the definition of a functional safety concept;

- Part 4: Product development at the system level – specifies the requirements for product development at system level;
- Part 5: Product development at the hardware level - specifies the requirements for product development at hardware level;
- Part 6: Product development at the software level - specifies the requirements for product development at software level;
- Part 7: Production and operation – specifies the requirements for production, operation and decommissioning services;
- Part 8: Supporting processes – specifies the requirements for support processes, such as documentation and qualification tools;
- Part 9: Automotive Safety Integrity Level (ASIL)-oriented and safety-oriented analyses – specifies the requirements for ASIL-oriented analysis and introduces the ASIL decomposition approach;
- Part 10: Guideline on ISO 26262 – overview of ISO 26262 as well as insights into the other parts of the standard.

Technological complexity is also on the rise so, there are increased risks from systematic failures and random hardware failures. ISO 26262 provides guidelines to avoid these risks, through appropriate requirements and processes.

System safety is achieved through safety measures, implemented in several technologies (mechanical, hydraulic, electrical...) and used in different levels of the development process. It provides a framework:

a) Provides an automotive safety lifecycle (management, development, production, operation, service, decommissioning) and supports the development of the necessary activities in these phases);
b) Provides automotive risk-based approach to determine ASILs;
c) Uses ASILs to specify requirements of ISO 26262 to avoid unreasonable residual risk;
d) Provides requirements for validation and confirmation measures to ensure an acceptable level of safety;
e) Provides requirements for relations with suppliers.

Functional safety is influenced by the development process (activities: requirements, specification, design, implementation, integration, verification, validation and configuration), the production, service and management processes.

In Figure 2-1, the structure of ISO 26262 is shown. Phases of product development are based on a V-model.

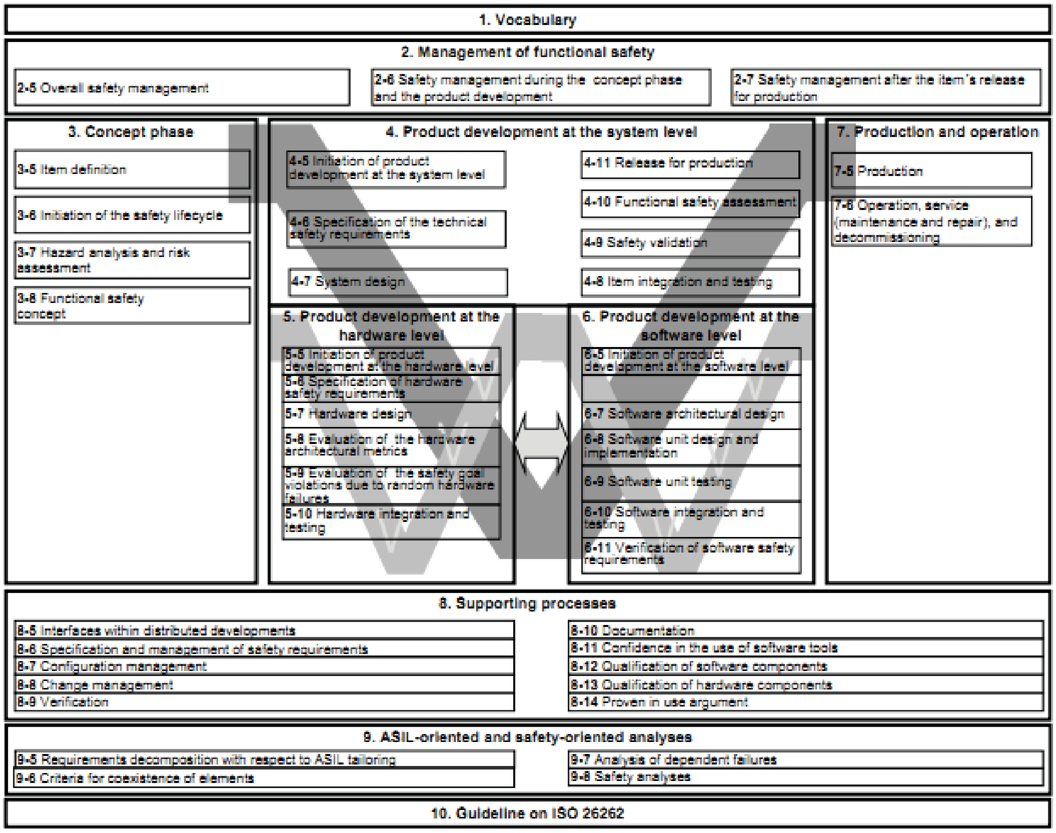

1. Vocabulary
2. Management of functional safety
2-5 Overall safety management
2-6 Safety management during the concept phase and the product development
2-7 Safety management after the item's release for production
3. Concept phase
3-5 Item definition
3-6 Initiation of the safety lifecycle
3-7 Hazard analysis and risk assessment
3-8 Functional safety concept
4. Product development at the system level
4-5 Initiation of product development at the system level
4-6 Specification of the technical safety requirements
4-7 System design
4-11 Release for production
4-10 Functional safety assessment
4-9 Safety validation
4-8 Item integration and testing
7. Production and operation
7-5 Production
7-6 Operation, service (maintenance and repair), and decommissioning
5. Product development at the hardware level
5-5 Initiation of product development at the hardware level
5-6 Specification of hardware safety requirements
5-7 Hardware design
5-8 Evaluation of the hardware architectural metrics
5-9 Evaluation of the safety goal violations due to random hardware failures
5-10 Hardware integration and testing
6. Product development at the software level
6-5 Initiation of product development at the software level
6-7 Software architectural design
6-8 Software unit design and implementation
6-9 Software unit testing
6-10 Software integration and testing
6-11 Verification of software safety requirements
8. Supporting processes
8-5 Interfaces within distributed developments
8-6 Specification and management of safety requirements
8-7 Configuration management
8-8 Change management
8-9 Verification
8-10 Documentation
8-11 Confidence in the use of software tools
8-12 Qualification of software components
8-13 Qualification of hardware components
8-14 Proven in use argument
9. ASIL-oriented and safety-oriented analyses
9-5 Requirements decomposition with respect to ASIL tailoring
9-6 Criteria for coexistence of elements
9-7 Analysis of dependent failures
9-8 Safety analyses
10. Guideline on ISO 26262

Figure 2-1: Overview of ISO 26262 [1]

2.2.2. ASILs

These are the integrity levels in ISO 26262, similar to SILs. There are 5 ASILs: QM (no integrity requirements), A, B, C and D (the highest safety requirement).

ASILs are assigned to hazards that may contribute to the violation of the safety goals, according to the following parameters:

- Severity of potential harm (S) – degree of physical damage caused to each endangered individual, including the driver, passengers and other traffic participants.

Table 2.1: Levels of Severity of Potential Harm [1]

S0	S1	S2	S3
No injuries	Light and moderate injuries	Severe and life-threatening injuries (survival probable)	Life-Threatening (survival uncertain), fatal injuries.

- Probability of exposure (E) – the frequency and how long individuals are exposed to the hazardous event.

Table 2.2: Levels of Probability of Exposure [1]

E0	E1	E2	E3	E4
Incredible	Very low probability	Low probability	Medium probability	High Probability

- Controllability (C) – the ability of the driver or other traffic participants

Table 2.3: Levels of controllability [1]

C0	C1	C2	C3
Controllable in general	Simply Controllable	Normally Controllable	Difficult to control or uncontrollable

Then the assigned ASIL to each hazard is inferred with the rules presented in table 2.4.

Table 2.4: ASIL assignment, function of Severity, Exposure and Controllability [1]

Severity class	Probability class	Controllability class		
		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

These ASILs will be used to figure out the target values for the hardware evaluation metrics that are going to be presented in chapter 3.

The events safety analysis have ASILs. The next section (2.3) introduces the two most important safety analysis techniques.

2.3. Classic safety analysis techniques: FTA and FMEA

FTA (Fault Tree Analysis) is a top-down (deductive) graphical representation of logical combinations of failures. It consists of a top event (system failure), connected to basic event(s) using logical gates, like AND or OR. Basic events generally are component failures or events expected to happen as normal operation of the system. The analysis is composed by two parts: qualitative (logical) and quantitative (probabilistic) analysis. The objective of the first is to reduce the logical expressions represented in the Fault Tree into a set of minimal cut sets, which are the smallest combination of failures required to cause the top event. Quantitative analysis is used to calculate the probability of the top event, with the probability of each of the basic events, this is only possible if the failure rate of the basic components is known [6].

FMEA is a bottom-up (inductive) technique, in which lists are compiled for all the possible failure modes, using failures of the various parts of the system to infer the effects on the rest of the system. These effects are usually evaluated according to a number of criteria, such as severity, probability and detectability that are then combined into an overall estimate of risk. All the information is combined in a table which allows to quickly see what the effects of each failure mode are [6].

Both techniques are useful and provide important information about the systems, but both suffer from the same flaw, they are manual techniques and the process to perform them can be difficult and time-demanding, especially for large and complex systems. This makes the whole process error prone or the results too numerous to interpret efficiently. Despite the manual process being still predominant, there have been for some time now tools that support the analysis, automating certain aspects of it [6].

2.4. Modern Safety Analysis Tools and Techniques

These appear as the need for automating parts or all the process of FTA and FMEA increases. There are two categories for these tools. The first is compositional safety analysis approach and consists in the development of formal and semi-formal languages to enable composition, specification and analysis of system failure behavior, based on safety information about the components. The majority of these tools are semi-automated, as they need manual entry of the components failure information and can be useful in a model-based design process (e.g.: HiP-HOPS). The second category involves more rigorous models to enable the analysis of the effects of failures by simulating them and checking if the system meets the safety goals. To achieve this, the tool adapts formal verification methods to support safety analysis [6].

2.4.1. Compositional Safety Analysis Techniques (CSA)

The first technique of this type is the Failure Propagation and Transformation Notation (FPTN), a graphical description of the failure behavior of the system. This uses component modules connected by inputs and outputs to other modules, allowing combination and propagation of failures, also they can be decomposed by subsystems. Its purpose is to create a connection between deductive FTA and inductive FMEA, in order to study cause and effect. The inconvenience is the need to create an error model separate from the system model that can become desynchronized from the original system. That being said, this technique is not used to system analysis or design optimization, but only for describing specifications of failure.

Next comes Fault Propagation and Transformation Calculus (FPTC) that links the failure model to the system model. It defines failure classes (e.g.: omission, commission and value errors) that are specified in annotations in the components of the system model. Then failure information is transmitted to the rest of the system by a set of expressions that detail how failures are transformed and propagated from input to output (mitigation is possible by transforming failure into natural behavior). This a “token-passing network”, determining the effects of component failure in the entire system. It also allows quantitative analysis by including probabilities in the expressions. The advantage over FPTN is the use of system models, so any small changes to it do not require a new failure model, but only the update of some failure expressions. The disadvantage is that FPTC is inductive, because it relies on injecting failures into the system, so it is difficult to achieve the information given by an FTA, also it is prone to combinatorial explosion.

Other techniques based on FPTN are State-Event Fault Trees (SEFTs) and Component Fault Trees (CFTs). The last technique is a failure logic of components defined graphically as interconnected Fault Trees, the HiP-HOPS tool is similar to this approach. These are not affected by combinatorial explosion as much as FPTC. SEFTs are based on CFTs and allow analysis of dynamic systems as it distinguishes between a system in a state (over a period of time) and an event that triggers a state transition (instantaneous). The failure behavior is modelled at component level, but enables the representation of sequences and allows negation (e.g.: event that has not happened yet) with the NOT gate. By being more complex, SEFTs can be analyzed with FTA, so it uses a conversion to Deterministic Stochastic Petri Nets (DSPNs).

2.5. Automatic optimization of system reliability

As said before, manual safety analysis to evaluate different designs is highly time-consuming and restricts the number of design candidates. This process needs to be automated, to examine the most potential designs and choose the best suited for the objectives (cost, time, quality...). Even with modern computers, it is not possible to evaluate the total design space, particularly if multiple methods of variability are taken into account (e.g.: swapping a system architecture for another and substituting one component with an alternative architecture). Another problem is the main concern of system designers, cost. A balance between the two conflicting goals of increasing reliability and cost reduction is required.

This section is just introductory, as HiP-HOPS allows the automatic optimization of system designs. However, it will not be further developed, as it is not truly important to this thesis.

2.5.1. Different optimization approaches

The goal of the optimization is to find optimal solutions without the problem of getting stuck in a local optimum. To reach this goal, there are different algorithms and almost all use meta-heuristics.

One of this algorithms is tabu search, which is based on evaluation functions (e.g.: if a solution has better characteristics, it is used for the next iteration), that can have multiple objectives. This algorithm has memory, to prevent looping or getting stuck in a local optimum (tabu solutions) [6].

Another technique is to use genetic algorithms. In this approach, a population of different candidates is evaluated and the best individuals are chosen to reproduce and form the basis of the next generation of candidates. Each one of these candidates has a genetic encoding, which encloses its characteristics, then happens the crossover of the encodings. Random mutation also happens to ensure a greater portion of search space and to avoid getting stuck in a local optimum. There are different forms of genetic algorithms, including penalty-based approach, in which the multiple objectives are combined into one function. One objective is optimized, but the others are imposed constraints and if infringed, a penalty is subtracted from the fitness score of the candidate. Another approach of genetic algorithms is the Non-Dominated Sorting

Genetic Algorithm (NSGA-II), a multi-objective technique which works by constructing a multi-dimensional graph, where the current solutions within a population are shown (Figure 2-2). Given a solution B, if a solution A is better in at least one objective and no worse in any of the others, then solution B is dominated by solution A. The Non-Dominated solutions are named Pareto front and they are the optimal solutions. These solutions represent trade-offs between all the objectives [6].

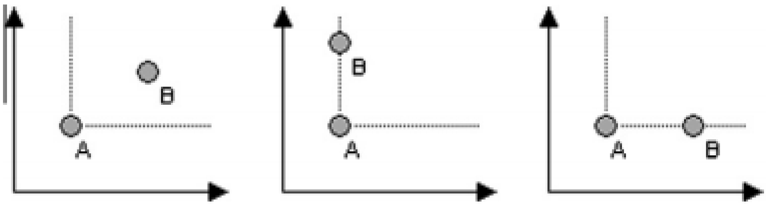


Figure 2-2: Dominated and Non-Dominated Solutions [6]

HiP-HOPS uses a modified version of the NSGA-II genetic algorithm technique.

2.6. HiP-HOPS and Safety Analysis

HiP-HOPS is a model-based semi-automatic compositional safety and reliability analysis tool that was created and continues to be further developed at the University of Hull by the Dependable Systems group. In these sections, the potentialities of the tool will be discussed and a brief example of its operation in combination with MatLab Simulink will be demonstrated.

2.6.1. HiP-HOPS as a state-of-the-art tool

HiP-HOPS requires a set of local component failure data in a system model, describing how combinations of internal failure modes and deviations at the components inputs generate output failures. Using that information, HiP-HOPS automatically synthesizes a network of interconnected Fault Trees which shows the propagation of failures through the system and a Failure Mode and Effects Analysis (FMEA) demonstrating component’s failure modes and their effects on high level system functionalities.

The capability of obtaining those results automatically is extremely important as the electronic systems tend to get more complex. The classical manual techniques tend to be performed only once, either after the system has been designed to check if it is reliable, or after the system is in operation and fails, to find out the error. This approach does not use the full potential of FTA or FMEA. The ideal scenario is to use FTA and FMEA during the design process itself, so that a system is designed with safety and reliability in mind. By executing safety analysis as part of an iterative process, it is possible to find and remedy potential flaws much earlier, saving time, effort and money and producing a better product.

HiP-HOPS can be used as soon as a system's concept can be turned into a model that identifies components and material, energy or data transactions amongst them. Models can be arranged hierarchically to deal with complexity. The tool can be used to analyse a variety of systems, such as fluidic, electrical, electronic or mechanical [3].

Other capabilities of HiP-HOPS that contribute to the field of dependability include:

- Temporal Fault Trees Generation:

It has become apparent that standard FTA and FMEA are poorly suited to analyse systems in which time plays an important role [11]. Those systems may have multiple states of operation, or a specific sequence of events may need to occur to originate a fault. To analyse the failure behaviour of those systems, multiple fault trees are usually created to account for each of the system's states. Another solution is to enclose the temporal constraints within event description. The two solutions can be unsatisfactory; the first can lead to complex and fragmented analysis and the second can hide important temporal relations [11]. To overcome the limitations of fault trees and FMEA concerning the referred systems, HiP-HOPS assesses sequences of failures via synthesis of temporal fault trees and FMEAs. This technique is a result of the integration of HiP-HOPS and Pandora. The latter is a method that enables modelling and analysis of dynamic failure behaviour systems via extensions to Boolean Logic [11].

- Multi-Objective optimization:

When there are various alternatives for a system's architecture, they must be assessed in accordance with the specific developer's interests. This is a difficult, multi-objective problem that can only be undertaken with the aid of computerized algorithms that allow effectively optimal solutions to be found in large design spaces [3]. HiP-HOPS is capable of evaluating a set of possible design alternatives according to user defined parameters such as cost and dependability. The assessment of the different solutions is performed using a multi-objective genetic algorithm that exploits the automated fault tree and FMEA synthesis algorithms in order to find Pareto optimal architectures. These represent the optimal trade-offs between the objective parameters considered by the system's designer [3].

HiP-HOPS has the capability to consider preventive maintenance to evaluate dependability and availability and through it, using also a genetic algorithm, the tool is capable of performing multi-objective optimization of preventive maintenance schedules [5].

- Linguistic concepts for representation and reuse of component failure patterns:

Well-established failure data can be stored in a library and reused posteriorly. This process saves time and effort and it can be seen as a means for analysts who are unfamiliar with a system to access viable information. Recurring patterns, like fail-silent behavior components, for example, are the most promising elements of this technique [9]. The limitation faced by the failure behavior reuse is the lack of a robust and machine-readable method to specify failure data [9]. HiP-HOPS has the capability to solve this problem using Generalized Failure Logic (GFL). Through a combination of Boolean Logic and generalized references to component ports and failure classes, GFL allows writing expressions that are applicable to multiple components with the same failure behavior, even if their interfaces differ [9].

2.6.2. Safety Analysis with HiP-HOPS

The HiP-HOPS safety analysis results in the capture of a system's behavior through the generation of fault trees (and posterior analysis) and FMEAs. This process is divided in three different stages [6]:

- 1st Modelling: system modelling and failure annotation;
- 2nd Synthesis: fault tree generation;
- 3rd Analysis: FTA and FMEA synthesis.

The three phases are described below.

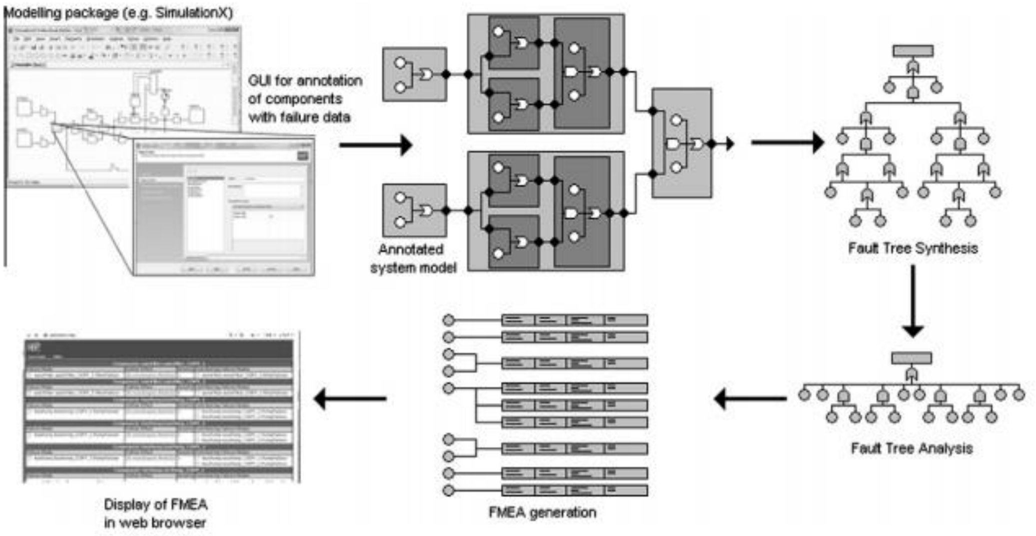

Modelling package (e.g. SimulationX)
GUI for annotation of components with failure data
Annotated system model
Fault Tree Synthesis
Fault Tree Analysis
FMEA generation
Display of FMEA in web browser

Figure 2-3: HiP-HOPS phases' overview [2]

2.6.2.1. Modelling Phase

This is the phase in the HiP-HOPS methodology that remains manual. To build fault trees, HiP-HOPS must be inputted with information about the relationships between components and the ways that they can fail [6]. The user has to provide this information on the system model. Currently, HiP-HOPS is capable of working with modelling tools such as Matlab Simulink, Eclipse-based UML tools and ITI SimulationX [6]. In the model, the sub-systems are conceptual blocks and data flow diagrams. Developing these models in a modular manner is important to allow easy modification and re-use in the future.

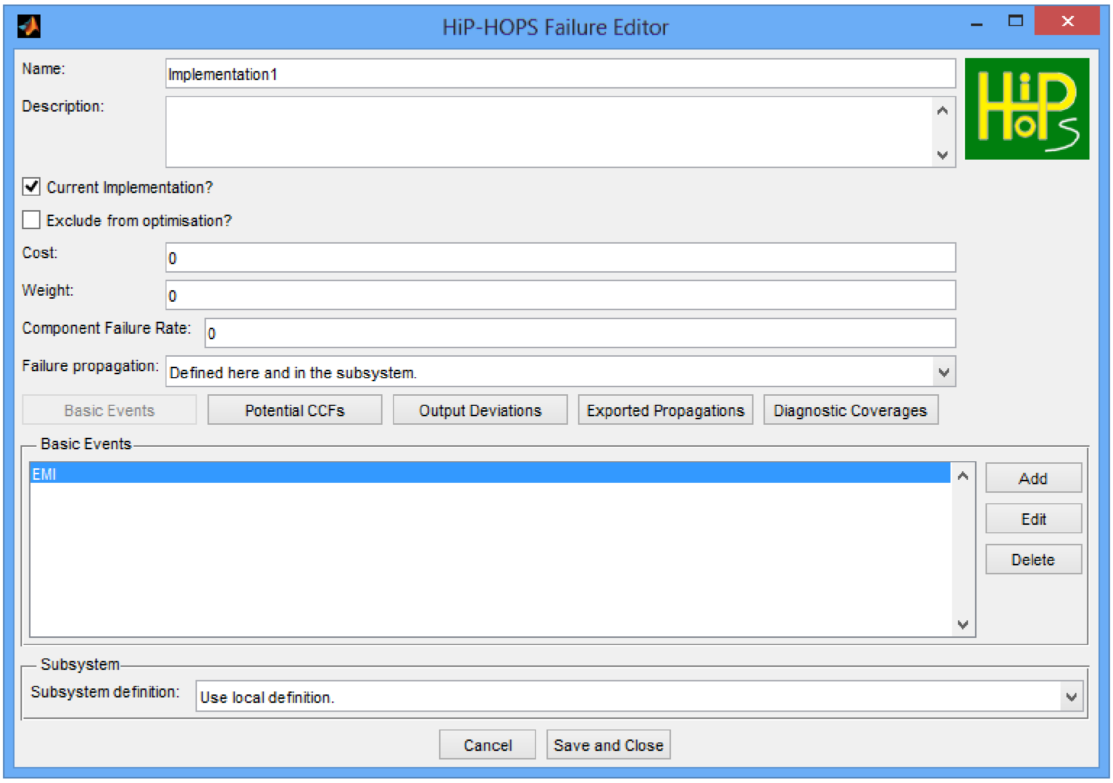
The component's or subsystem's failure data is a set of logical expressions that express how their outputs can be deviated. Those logical failure expressions should include information about the component's internal failures (basic events in the fault trees) and the inputs that hold any type of deviation. The type of deviations can differ, for instance, they can be related to a component failing to provide an output when requested (omission) or providing one, when it was not requested (commission); deviations of value also exist, with either outputs with a different value (higher or lower) than the correct one or temporarily incorrect (late or early). As said before, the set of logical expressions used to illustrate the component's failure behavior, can be stored and re-used. A generalized example of a component's commission deviated output is presented below:

$$Commission - Out1 = (Commission - In1\ AND\ Commission - In2) OR\ InternalFailure1$$

The Commission of output1 (Out1) is caused either by the combination of the Commission of input1 and input2 or by an internal failure of the component.

Generalizing the HiP-HOPS terminology rules:

- Inputs and outputs: "type of deviation" - "name of the I/O in the model";
- Internal failures can assume the form of valid identifiers. For example: "short circuit".



Name: Implementation1

Description:

☑ Current Implementation?

☐ Exclude from optimisation?

Cost: 0

Weight: 0

Component Failure Rate: 0

Failure propagation: Defined here and in the subsystem.

Basic Events

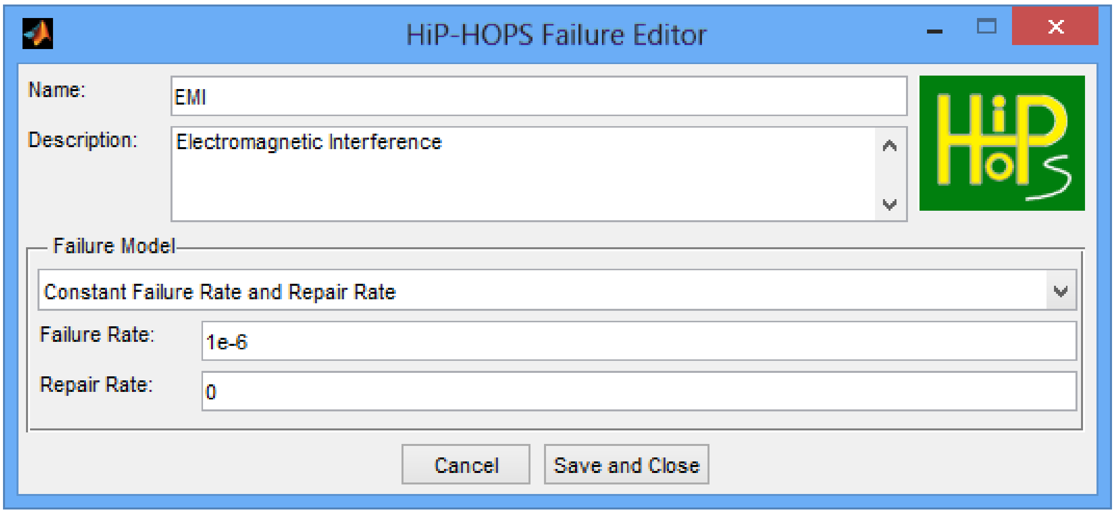
EMI

Subsystem

Subsystem definition: Use local definition.

Figure 2-4: Matlab Component Failure Editor [2]

So, to begin component failure annotation, the user must select the component and open the failure editor, seen in figure 2-4. Then then component's internal failures or basic events can be added. In this example, the component has one basic event, named EMI (Electro Magnetic Interference - Figure 2-5).



Name: EMI

Description: Electromagnetic Interference

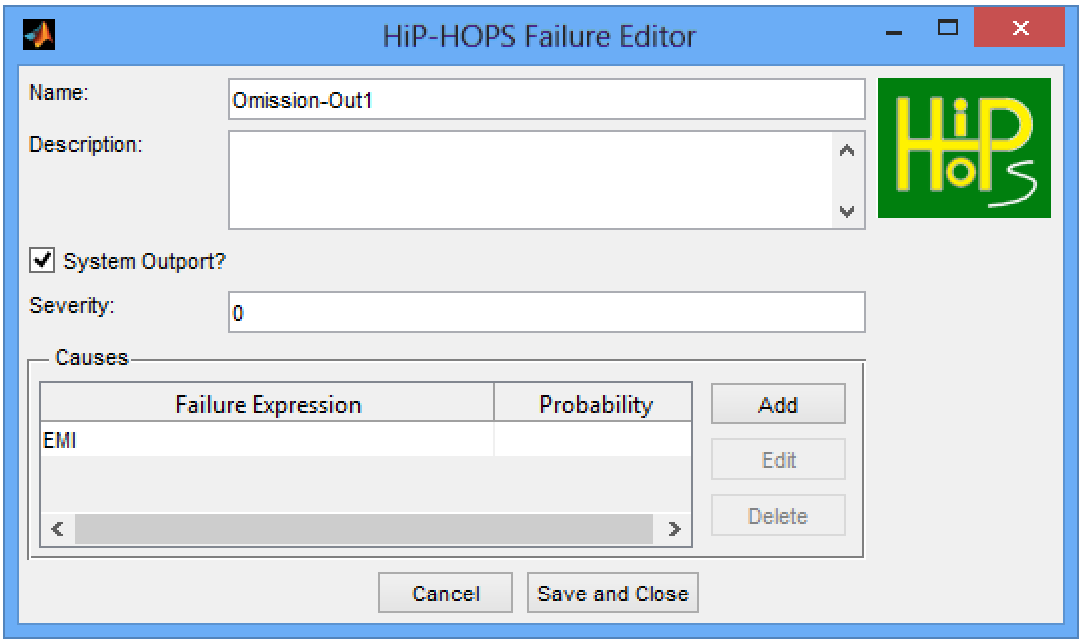
Failure Model: Constant Failure Rate and Repair Rate

Failure Rate: 1e-6

Repair Rate: 0

Figure 2-5: Inserting a component's basic event [2]

The following step is to insert the failure expressions for the component's output deviations. In this case, the output deviation of the component is an omission, caused just by its internal failure,



Name: Omission-Out1

Description:

☑ System Outport?

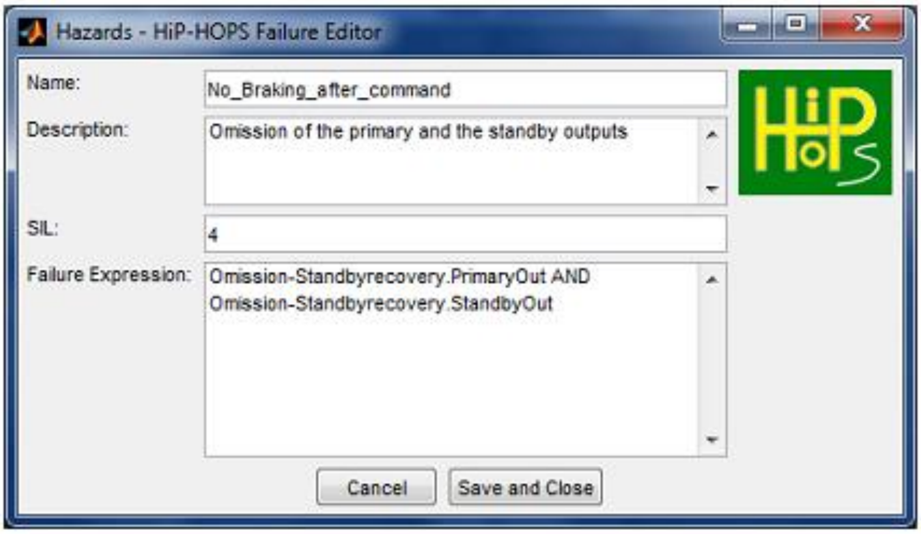
Severity: 0

Causes

Failure Expression	Probability
EMI	

Figure 2-6: Inserting a component's output deviation [2]

This is also the phase, when the system's output ports should be identified, as they will relate to the top events (hazards) of the fault trees generated in the synthesis phase. In case of SIL usage, hazards must be identified and assigned SILs. These can be associated with one or several of the system's output ports. Figure 2-7 shows an example of hazard annotation. This hazard occurs with the combination of the two system output ports and has a level 4 SIL.



Name: No_Braking_after_command

Description: Omission of the primary and the standby outputs

SIL: 4

Failure Expression: Omission-Standbyrecovery.PrimaryOut AND Omission-Standbyrecovery.StandbyOut

Figure 2-7: Creation of a Hazard for the system [2]

2.6.2.2. Synthesis Phase

The second phase is the fault tree synthesis. HiP-HOPS automatically creates a set of fault trees with the system's output port deviations as the top events or, in case of SIL allocation, the system's hazards, by combining failure data for individual components and sub-systems. The result is a network of interconnected fault trees, which define the relationships between failures of system outputs and their causes in the failure of components. This is a deductive process, working backwards from system outputs to determine which individual components cause those failures with logical combinations, such AND and OR ports.

The generated component fault trees are then combined into one fault tree per deviated output or hazard. These fault trees can then be read by the software Isograph Fault Tree++, to make the visualization clearer.

2.6.2.3. Analysis Phase

In the second phase, the result of the synthesis process is one or more interconnected Fault Trees, so the next stage is to analyse them using FTA. Fault Trees tend to be large and complex, so by reducing them to their minimal cut-sets, we have the relationship between the minimal combinations of basic events that lead to the top level failure, without the intermediate propagation paths. [2]

The cut-set generating algorithm used by HiP-HOPS is a modified MICSUP (Minimal Cut Sets Upwards), it is a bottom-up algorithm. [2]

The following Boolean laws are applied to obtain the minimal cut-sets:

NOTE: "E1" and "E2" represent basic event 1 and basic event 2.

- Law of absorption:

$$E1 + E1.E2 = E1$$

The cut set “E1.E2” was removed as the event “E1” alone is sufficient to cause the top event. [2]

- Laws of idempotence:

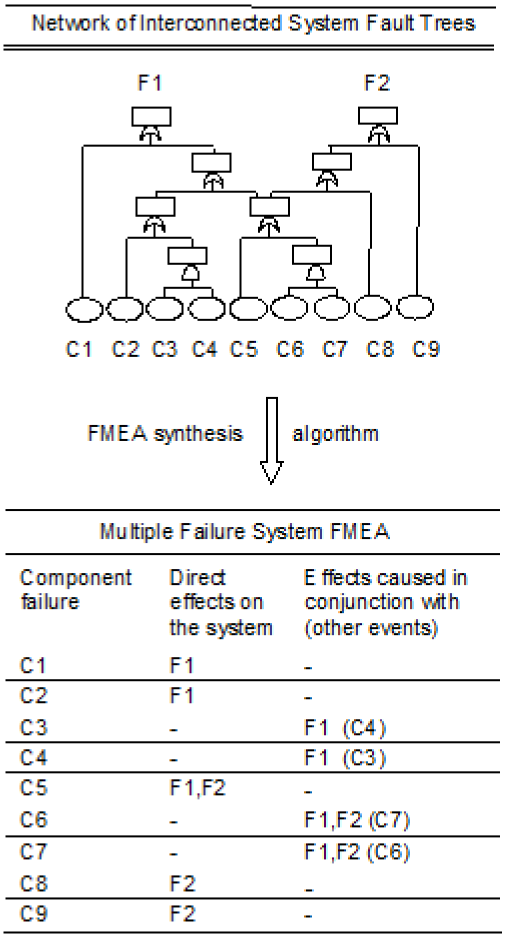
$$\mathrm{E1.E1} = \mathrm{E1}$$

Repeated events in the same cut-set are removed [2].

$$E1 + E1 = E1$$

Repeated cut-sets are removed [2].

Once the minimal cut-sets are identified, HiP-HOPS uses the results to perform the allocation of safety integrity levels; also, a qualitative analysis can be applied to generate FMEAs. The minimal cut sets have the non-redundant propagation of failure in the fault tree and an algorithm is used to catalogue each component failure mode and note which system failure they cause [2]. The FMEA shows the direct relationship between component failures and system failures, so it is possible to quickly verify how a failure of a given component affects everything else in the system and the likelihood of that happening. A classic FMEA only shows the direct effects of single failure modes, but because HiP-HOPS FMEA’s is generated from Fault Trees, the further effects of the failure are also shown. This concept is illustrated in figure 2-8 [2].



Multiple Failure System FMEA

Component failure	Direct effects on the system	Effects caused in conjunction with (other events)
C1	F1	-
C2	F1	-
C3	-	F1 (C4)
C4	-	F1 (C3)
C5	F1,F2	-
C6	-	F1,F2 (C7)
C7	-	F1,F2 (C6)
C8	F2	-
C9	F2	-

Figure 2-8: Conversion of Fault Trees to FMEA [2]

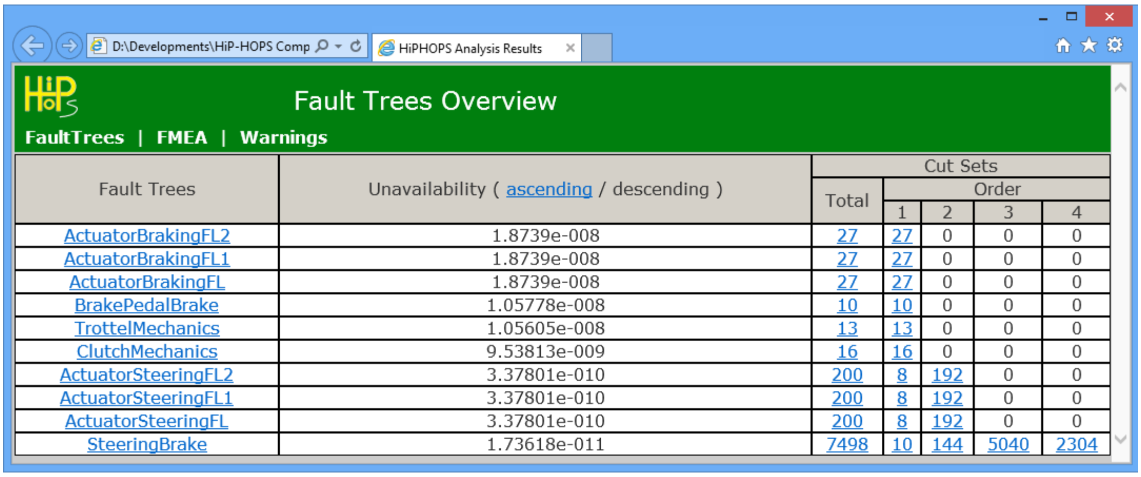
In Figure 2-8, “F1” and “F2” are system Failures and “C1” to “C9” are component Failures. For “C3”, “C4”, “C6” and “C7” there are no direct effects on the system, but only if a single one of this components fails, if, for example, “C3” and “C4” both happen, “F1” will occur.

A quantitative analysis can also be done, to calculate the system unavailability, Q_S (if basic events have quantitative data [2]):

$$Q_S = 1 - \prod_{i=1}^{n} (1 - Q_{CSi})$$

$$n - number\ of\ independent\ cut\ sets$$
$$Q_{CSi} - unavailability\ of\ the\ cut\ set\ i$$

The resultant fault trees, cut sets, FMEAs and SIL allocations are presented in html format. Currently, the files generated can only be opened with Internet Explorer [16].

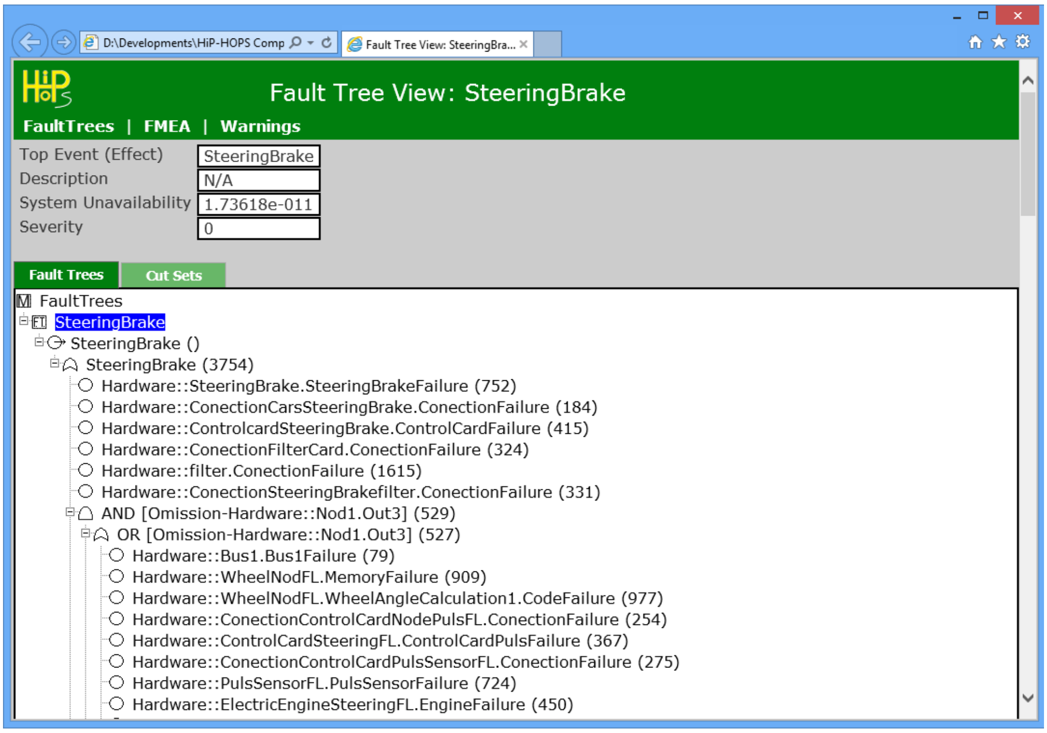


Fault Trees Overview

Fault Trees	Unavailability (ascending / descending)	Cut Sets				
		Total	Order			
			1	2	3	4
ActuatorBrakingFL2	1.8739e-008	27	27	0	0	0
ActuatorBrakingFL1	1.8739e-008	27	27	0	0	0
ActuatorBrakingFL	1.8739e-008	27	27	0	0	0
BrakePedalBrake	1.05778e-008	10	10	0	0	0
TrottelMechanics	1.05605e-008	13	13	0	0	0
ClutchMechanics	9.53813e-009	16	16	0	0	0
ActuatorSteeringFL2	3.37801e-010	200	8	192	0	0
ActuatorSteeringFL1	3.37801e-010	200	8	192	0	0
ActuatorSteeringFL	3.37801e-010	200	8	192	0	0
SteeringBrake	1.73618e-011	7498	10	144	5040	2304

Figure 2-9: Fault tree analysis summary [2]

Each fault tree has a name, which is constructed from the name of the output deviation they come from. Clicking on a fault tree name opens that fault tree results (figure 2-10) [2].


D:\Developments\HiP-HOPS Comp
Fault Tree View: SteeringBra...
FaultTrees | FMEA | Warnings
Fault Trees
Cut Sets

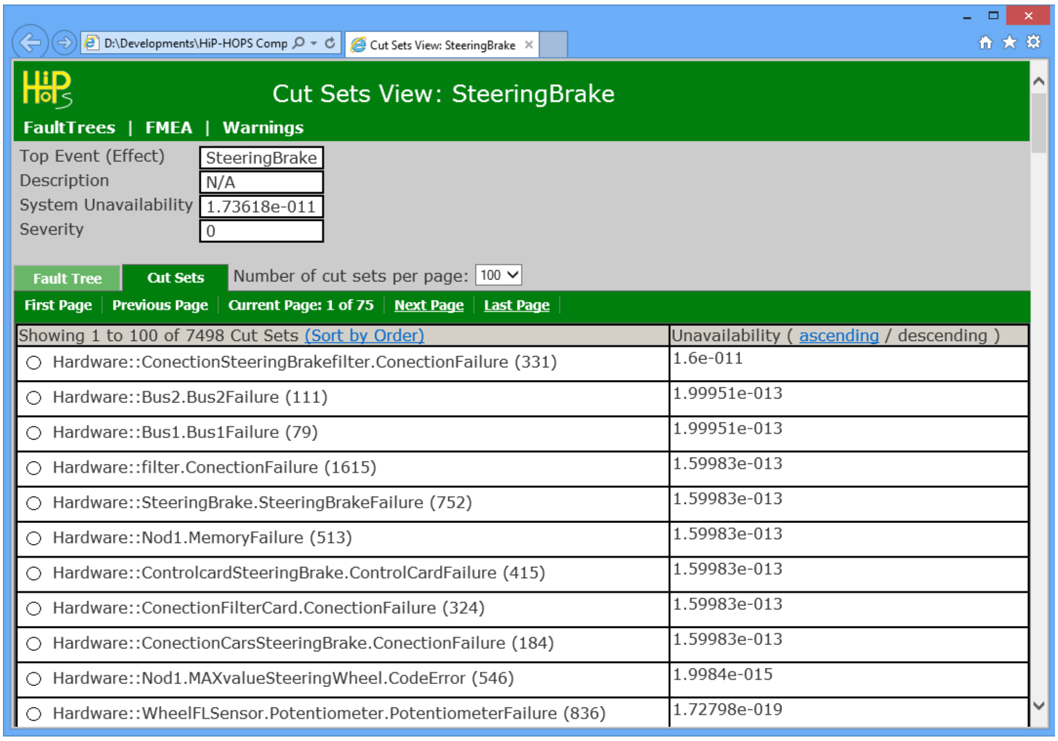
Fault Tree View: SteeringBrake

Top Event (Effect): SteeringBrake
Description: N/A
System Unavailability: 1.73618e-011
Severity: 0

```
FaultTrees
 SteeringBrake
  SteeringBrake ()
   SteeringBrake (3754)
    Hardware::SteeringBrake.SteeringBrakeFailure (752)
    Hardware::ConectionCarsSteeringBrake.ConectionFailure (184)
    Hardware::ControlcardSteeringBrake.ControlCardFailure (415)
    Hardware::ConectionFilterCard.ConectionFailure (324)
    Hardware::filter.ConectionFailure (1615)
    Hardware::ConectionSteeringBrakefilter.ConectionFailure (331)
    AND [Omission-Hardware::Nod1.Out3] (529)
     OR [Omission-Hardware::Nod1.Out3] (527)
      Hardware::Bus1.Bus1Failure (79)
      Hardware::WheelNodFL.MemoryFailure (909)
      Hardware::WheelNodFL.WheelAngleCalculation1.CodeFailure (977)
      Hardware::ConectionControlCardNodePulsFL.ConectionFailure (254)
      Hardware::ControlCardSteeringFL.ControlCardPulsFailure (367)
      Hardware::ConectionControlCardPulsSensorFL.ConectionFailure (275)
      Hardware::PulsSensorFL.PulsSensorFailure (724)
      Hardware::ElectricEngineSteeringFL.EngineFailure (450)
```

Figure 2-10: Fault tree results [2]

The user can also see the cut-sets of basic events that cause the hazard or output deviation and the FMEA results. Figure 2-11 shows an example of cut-set results and figure 2-12 an example of a FMEA table.



Cut Sets View: SteeringBrake

FaultTrees | FMEA | Warnings

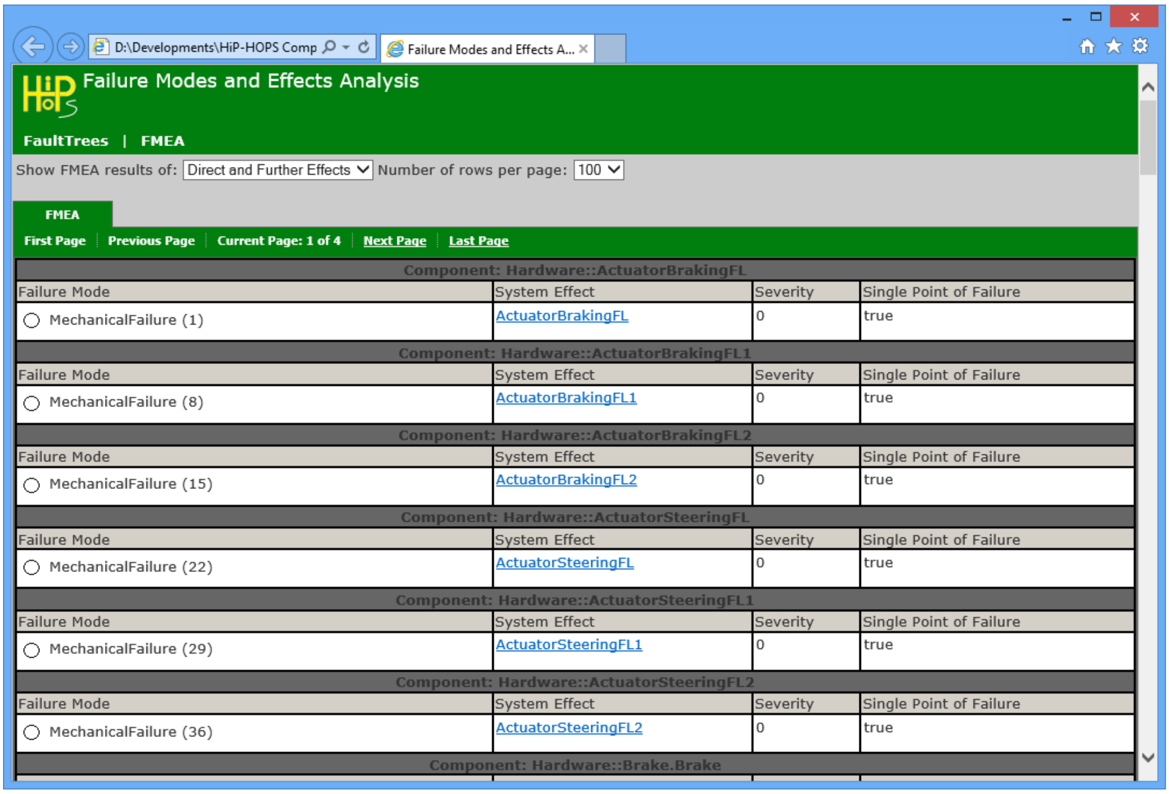
Top Event (Effect) SteeringBrake
Description N/A
System Unavailability 1.73618e-011
Severity 0

Number of cut sets per page: 100

First Page | Previous Page | Current Page: 1 of 75 | Next Page | Last Page

Showing 1 to 100 of 7498 Cut Sets (Sort by Order)	Unavailability (ascending / descending)
○ Hardware::ConectionSteeringBrakefilter.ConectionFailure (331)	1.6e-011
○ Hardware::Bus2.Bus2Failure (111)	1.99951e-013
○ Hardware::Bus1.Bus1Failure (79)	1.99951e-013
○ Hardware::filter.ConectionFailure (1615)	1.59983e-013
○ Hardware::SteeringBrake.SteeringBrakeFailure (752)	1.59983e-013
○ Hardware::Nod1.MemoryFailure (513)	1.59983e-013
○ Hardware::ControlcardSteeringBrake.ControlCardFailure (415)	1.59983e-013
○ Hardware::ConectionFilterCard.ConectionFailure (324)	1.59983e-013
○ Hardware::ConectionCarsSteeringBrake.ConectionFailure (184)	1.59983e-013
○ Hardware::Nod1.MAXvalueSteeringWheel.CodeError (546)	1.9984e-015
○ Hardware::WheelFLSensor.Potentiometer.PotentiometerFailure (836)	1.72798e-019

Figure 2-11: Cut-set results [2]



Failure Modes and Effects Analysis

FaultTrees | FMEA

Show FMEA results of: Direct and Further Effects Number of rows per page: 100

First Page | Previous Page | Current Page: 1 of 4 | Next Page | Last Page

Failure Mode	System Effect	Severity	Single Point of Failure
Component: Hardware::ActuatorBrakingFL			
○ MechanicalFailure (1)	ActuatorBrakingFL	0	true
Component: Hardware::ActuatorBrakingFL1			
○ MechanicalFailure (8)	ActuatorBrakingFL1	0	true
Component: Hardware::ActuatorBrakingFL2			
○ MechanicalFailure (15)	ActuatorBrakingFL2	0	true
Component: Hardware::ActuatorSteeringFL			
○ MechanicalFailure (22)	ActuatorSteeringFL	0	true
Component: Hardware::ActuatorSteeringFL1			
○ MechanicalFailure (29)	ActuatorSteeringFL1	0	true
Component: Hardware::ActuatorSteeringFL2			
○ MechanicalFailure (36)	ActuatorSteeringFL2	0	true
Component: Hardware::Brake.Brake			

Figure 2-12: FMEA table [2]

2.7. Summary

In this chapter it became clear that safety analysis plays a major role in hardware development, and that with the increasing complexity of E/E/EP systems, automatic safety analysis tools like HiP-HOPS are increasingly important to produce more reliable products. It was also evident how easy it is to use HiP-HOPS.

HiP-HOPS lacks some of the ideas and rules in ISO 26262, for hardware architecture evaluation. The next chapter will be an in-depth analysis of ISO 26262 – part 5, particularly, how are safety mechanisms modelled according to the standard and how to use the hardware verification metrics present there.

Chapter 3

Hardware evaluation techniques

This chapter is a full analysis of ISO 26262 – part 5: product development at hardware level. The intention is to understand how safety mechanisms should be modelled according to the standard and what hardware evaluation metrics are. Then, changes to HiP-HOPS will be proposed, to accommodate these concepts.

3.1. Introduction

This part of the standard specifies requirements for product development at hardware level for automotive applications, such as [1]:

- Requirements for the initiation of product development;
- Specification of the hardware safety requirements;
- Hardware design;
- Hardware architectural metrics;
- Evaluation of violation of the safety goal due to random hardware failures.

This requirements are applicable to non-programmable and programmable elements, like FPGA and PLD [1].

The steps required for the product development process, according to ISO 26262, are resumed in figure 3-1. The phases, especially explored in this thesis, are highlighted, “evaluation of the hardware architectural metrics” and “evaluation of safety goal violations due to random hardware failures”. There are two sections dedicated to those phases, sections 8 and 9 in ISO 26262 – part 5, which describe two alternatives to evaluate if the residual risk of safety goal violations is sufficiently low. They accomplish this by either using a global probabilistic approach or by using a cut-set analysis to study the impact of each identified fault of a hardware element upon the violation of the safety goals [1].

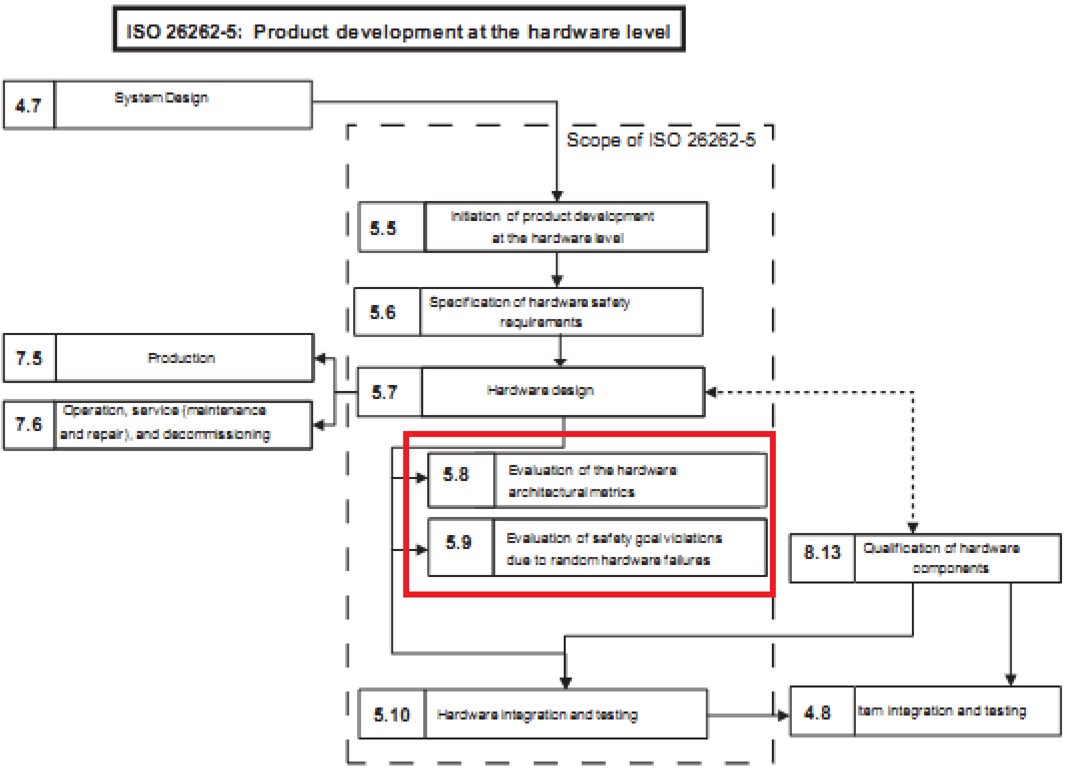

ISO 26262-5: Product development at the hardware level
4.7
System Design
Scope of ISO 26262-5
5.5
Initiation of product development at the hardware level
5.6
Specification of hardware safety requirements
7.5
Production
5.7
Hardware design
7.6
Operation, service (maintenance and repair), and decommissioning
5.8
Evaluation of the hardware architectural metrics
5.9
Evaluation of safety goal violations due to random hardware failures
8.13
Qualification of hardware components
5.10
Hardware integration and testing
4.8
Item integration and testing

Figure 3-1: Steps of product development at hardware level

3.2. Safety Mechanisms

Following the ISO 26262 product development method, the designer has to specify hardware safety requirements, which are no more than design constraints. These safety requirements shall include:

- Safety mechanisms to control relevant internal failures of the hardware element;
- Safety mechanisms to ensure the element is tolerant to external failures;
- Safety Mechanisms to detect and signal internal or external failures, to prevent faults from being latent;
- Other requirements not related to safety mechanisms that assure the avoidance of dangerous behaviour.

3.2.1. Safety Mechanisms Definition

According to ISO 26262, a **Safety Mechanism** is a technical solution implemented by E/E functions or elements, or by other technologies, to detect faults or control failures in order to achieve or maintain a safe state [1]. Safety mechanisms are implemented to prevent faults from leading to single-point failures or to reduce residual failures and to prevent faults from being latent [1]. Random hardware failures (relevant in this case) result from aging/wear-out, aggressive environment and manufacturing process variations.

Currently there is little work and tools that quantify the effect of the safety mechanisms and make use of the ISO 26262 architectural metrics. In the design phase, design choices should be compared with the safety mechanisms included, as these contribute to the final failure rate of the system. In ISO 26262-part 5, safety mechanisms are recommended to certain component faults.

Other important concepts, related to Safety Mechanisms are presented below:

- Diagnostic Coverage: “proportion of the hardware element failure rate that is detected or controlled by the implemented safety mechanisms [1]”;

3.2.2. Choice of Safety Mechanisms

ISO 26262 offers a guideline to choose appropriate safety mechanisms to be implemented in the E/E architecture to detect failures of elements [1].

The Annex D, in ISO 26262 part 5 is intended to be used as [1]:

a) An evaluation of the Diagnostic Coverage to produce a rationale for:
    1) The compliance with the single-point and latent faults metrics;

    2) The compliance with the evaluation of the safety goal violations due to random hardware failures:

b) A guideline in order to choose appropriate safety mechanisms to be implemented in the E/E architecture to detect failures of elements. [1]

Table 3.1 is an extract of Table D.1 in ISO 26262 part 5, which shows typical faults of the hardware elements of a generic embedded system (Figure 3-2) and provides guidelines which are adapted based on analysis of the system elements.

Three levels of achievable diagnostic coverage are considered: low- 60%, medium- 90% and high- 99%. Then Table D.1 indicates, for each element, the table (table D.2 to D.14) where guidelines for safety mechanisms are given. Other techniques can be used, if provided evidence is available to support the claimed diagnostic coverage. [1]

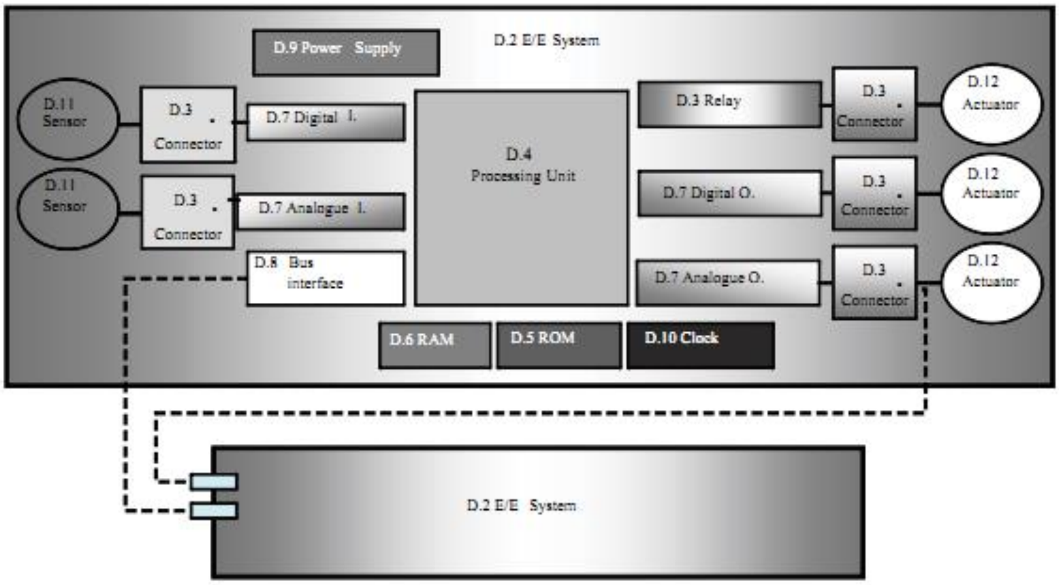
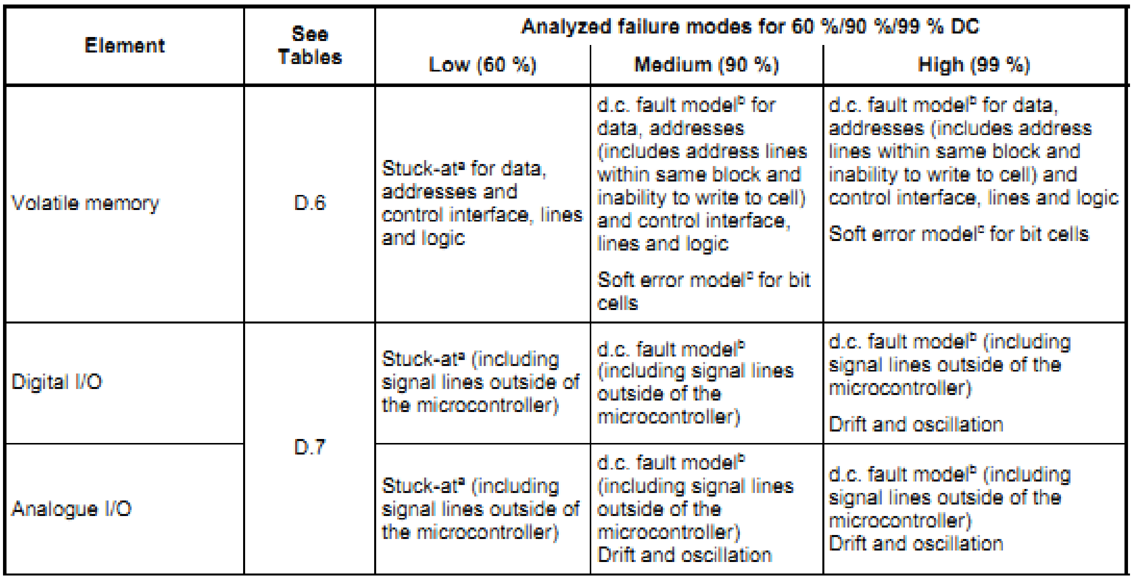


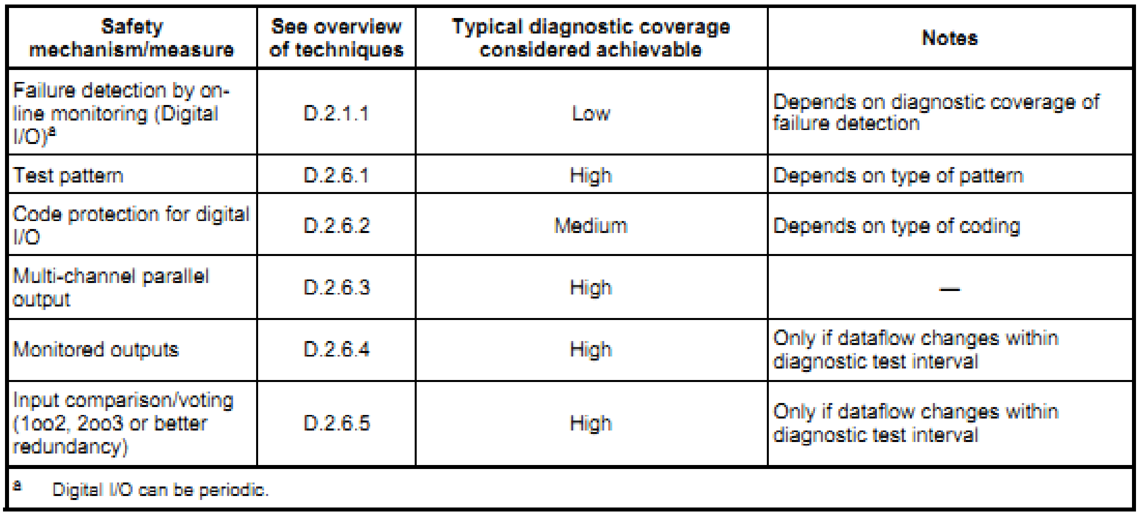
Figure 3-2: Generic Embedded System [1]

Table 3.1: Extract of table D.1 in ISO 26262- Analysed faults or failures modes in the derivation of diagnostic coverage [1]



Element	See Tables	Analyzed failure modes for 60 %/90 %/99 % DC		
		Low (60 %)	Medium (90 %)	High (99 %)
Volatile memory	D.6	Stuck-at[a] for data, addresses and control interface, lines and logic	d.c. fault model[b] for data, addresses (includes address lines within same block and inability to write to cell) and control interface, lines and logic Soft error model[c] for bit cells	d.c. fault model[b] for data, addresses (includes address lines within same block and inability to write to cell) and control interface, lines and logic Soft error model[c] for bit cells
Digital I/O	D.7	Stuck-at[a] (including signal lines outside of the microcontroller)	d.c. fault model[b] (including signal lines outside of the microcontroller)	d.c. fault model[b] (including signal lines outside of the microcontroller) Drift and oscillation
Analogue I/O		Stuck-at[a] (including signal lines outside of the microcontroller)	d.c. fault model[b] (including signal lines outside of the microcontroller) Drift and oscillation	d.c. fault model[b] (including signal lines outside of the microcontroller) Drift and oscillation

Table 3.2: Table D.7 in ISO 26262- Recommended Safety Mechanisms for Analogue and Digital I/O [1]



Safety mechanism/measure	See overview of techniques	Typical diagnostic coverage considered achievable	Notes
Failure detection by on-line monitoring (Digital I/O)[a]	D.2.1.1	Low	Depends on diagnostic coverage of failure detection
Test pattern	D.2.6.1	High	Depends on type of pattern
Code protection for digital I/O	D.2.6.2	Medium	Depends on type of coding
Multi-channel parallel output	D.2.6.3	High	—
Monitored outputs	D.2.6.4	High	Only if dataflow changes within diagnostic test interval
Input comparison/voting (1oo2, 2oo3 or better redundancy)	D.2.6.5	High	Only if dataflow changes within diagnostic test interval

[a] Digital I/O can be periodic.

After choosing the Safety Mechanism technique for the indicated elements, ISO 26262 provides an overview of that technique. The next few lines contain an extract of those overviews, for different types of elements.

For electrical elements, such as relays or sensors, the common safety mechanism selected for this study is the Comparator [1]:

- Aim: To detect (non-simultaneous) failures in independent hardware or software.
- Description: The output signals of independent hardware are compared cyclically or continuously by a comparator. For example, two processing units exchange data reciprocally. A comparison is carried out using software in each unit and detected differences lead to a failure message.

Processing Units are some of the most complex elements in a hardware architecture, they can have hardware or software safety mechanisms, sometimes even both. I have selected the self-test supported by hardware [1]:

- Description: additional special hardware to support self-test functions to detect failures in the processing unit and other sub-elements (e.g.: EDC coder/decoder) at a gate level. Typically it only runs at the initialization or power-down of the processing unit due to its intrusive nature. It is usually used for multipoint fault detection.
- Example: For sub-elements like EDC coders/decoders, a special HW mechanism (e.g.: logic BIST) can be added to generate inputs to the coder-decoder and check the results. These inputs are usually generated by pattern generators (e.g. MISR).

NOTE: Logic BIST - Logic built-in self-test (or LBIST) is a form of built-in self-test (BIST) in which hardware and/or software is built into integrated circuits allowing them to test their own operation, as opposed to reliance on external automated test equipment.

For actuators, the example is a technique named Monitoring [1]:

- Aim: detect incorrect operation of an actuator
- Description: The operation of the actuator is monitored. Can be done at the actuator level by physical parameter measurements but also at system level regarding the actuator failure effect.
- Example: A cooling fan, monitoring at system level uses a temperature sensor to detect failure. Monitoring of physical parameters measures the voltage, current or both on the inputs of the cooling fan.

3.2.3. How to Model Safety Mechanisms

In the sections above, safety mechanisms were introduced and examples of guidelines to properly select them according to the E/E element in cause were given. The remaining issue is how a designer can model a safety mechanism in a system model.

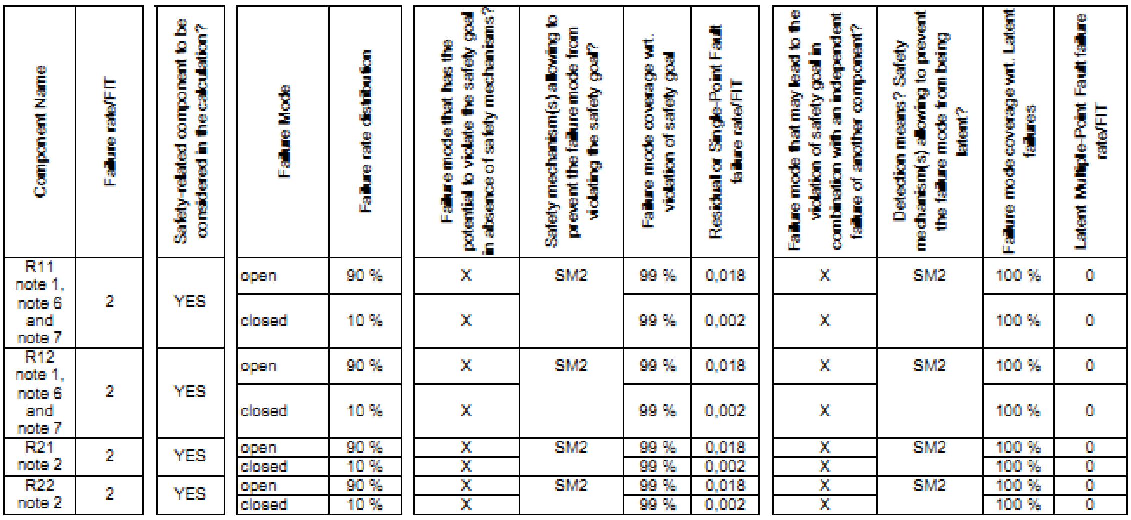
ISO 26262 - part 5, annex E is an example of metrics calculation. That example can help understand, along with other parts of the standard, the constraints of safety mechanism design.

The following conclusions were reached concerning safety mechanism insertion in system's models:

- One Safety Mechanism can cover several failure modes of different components, considered in the safety analysis for the same safety goal.

This point is evident in Table 3.3. SM2 (safety mechanism 2) is a comparator that compares the values of two inputs. The components that are covered by that safety mechanism influence, somehow, the values checked by it;

Table 3.3: Extract of Figure E.3 in ISO 26262 – part 5, annex E



Component Name	Failure rate/FIT	Safety-related component to be considered in the calculation?	Failure Mode	Failure rate distribution	Failure mode that has the potential to violate the safety goal in absence of safety mechanisms?	Safety mechanism(s) allowing to prevent the failure mode from violating the safety goal?	Failure mode coverage wrt. violation of safety goal	Residual or Single-Point Fault failure rate/FIT	Failure mode that may lead to the violation of safety goal in combination with an independent failure of another component?	Detection means? Safety mechanism(s) allowing to prevent the failure mode from being latent?	Failure mode coverage wrt. Latent failures	Latent Multiple-Point Fault failure rate/FIT
R11 note 1, note 6 and note 7	2	YES	open	90 %	X	SM2	99 %	0,018	X	SM2	100 %	0
			closed	10 %	X		99 %	0,002	X		100 %	0
R12 note 1, note 6 and note 7	2	YES	open	90 %	X	SM2	99 %	0,018	X	SM2	100 %	0
			closed	10 %	X		99 %	0,002	X		100 %	0
R21 note 2	2	YES	open	90 %	X	SM2	99 %	0,018	X	SM2	100 %	0
			closed	10 %	X		99 %	0,002	X		100 %	0
R22 note 2	2	YES	open	90 %	X	SM2	99 %	0,018	X	SM2	100 %	0
			closed	10 %	X		99 %	0,002	X		100 %	0

- Safety Mechanisms should have a flexible description, regarding its particular attributes, as they can assume different forms (software, hardware, different algorithms…) [10];
- The applicability of specific safety mechanisms to a certain component has to be resolved by component class hierarchy [10];
- Architectural evolution must be considered by safety mechanisms [10];
- A safety mechanism can be a component or a part of a component. For example, a microcontroller can have self-check hardware in its architecture or an external watchdog.

In [10] the authors propose an interesting way to model safety mechanisms. They consider a model represented by a set of computing nodes, where functional networks are responsible for the execution of each item and network or bus connections between those [10]. A node is modelled by a list of component and a list of safety mechanism instances [{Cj}, {SMk}]. A component Ci is a source of a set of failure effects $\{FE_{Cj,k}\}$ that can lead to the violation of the safety goal on the top level. These failure effects are included into the Component's faultHypotesis. A failure effect FE can be caused by a number of different failure modes {FMi}, which are associated by FaultHypothesis with a fraction $K_{FMi,Cj}$ as percentage of the failure rate for an effect caused by a specific failure mode [10].

A safety mechanism is modelled as possessing one or more detection capabilities. An object of the class DetectionCapability characterizes mechanism's coverage DC of specific failure modes, of specific component classes CC, that can be represented by [{CCi, FMi, DCi}]. When a safety mechanism is instantiated in a model, it is applied to one or more components by adding it to the mechanismsApplied reference list, or to the implicitMechanisms reference list, if the SM is implicit to that component [10].

The proposed metamodel, described by the paragraphs above can be seen in figure 3-3.

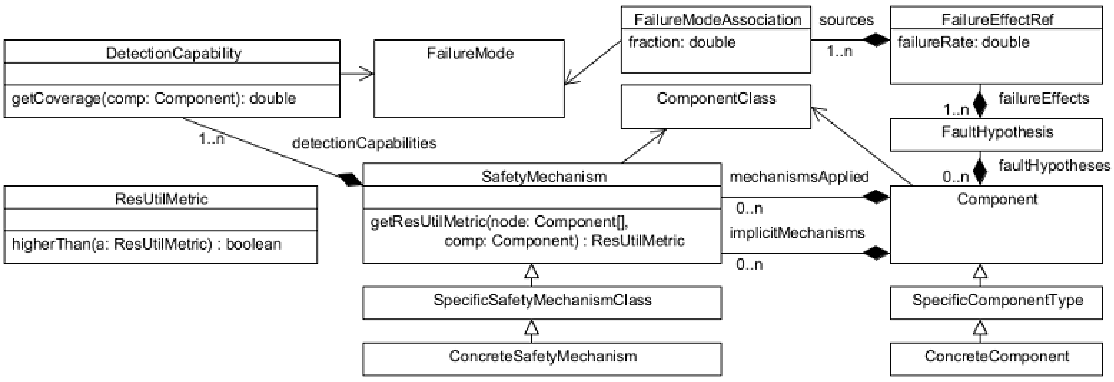


Figure 3-3: MetaModel for the safety mechanisms implementation proposed in [10]

The next chapter will contain a detailed explanation of how safety mechanisms were exactly modelled in the system model to account for the hardware evaluation metrics and for fault tree analysis with HiP-HOPS.

3.3. Fault classification of a hardware element

Before being able to evaluate hardware architectures through the metrics or safety goal violations by the other methods, the user must know how to classify hardware failure modes.

There are six different types of faults in a component:

- Safe Fault: “fault whose occurrence will not significantly increase the probability of violation of a safety goal [10]”;
- Single Point Fault (SPF): “fault in an element that is not covered by a safety mechanism and that leads directly to the violation of a safety goal [1]”;
- Residual Fault: “portion of a fault that by itself leads to the violation of a safety goal, occurring in a hardware element, where that portion of the fault is not covered by safety mechanisms [1]”;
- Multiple-Point Fault (MPF): “individual fault that, in combination with other independent faults, leads to a multiple-point failure [1]”;
    - Detected MPF: “Multiple-Point Fault that is detected, within a prescribed time, by a safety mechanism, that prevents it from being Latent;
    - Perceived MPF: “Multiple-Point Fault whose presence is deducted by the driver within a prescribed time interval”;
    - Latent MPF: “Multiple-Point Fault whose presence is not detected by a safety mechanism nor perceived by the driver within the multiple-point fault detection interval [1]”;

NOTE 1: Multiple-Point fault detection interval: “time span to detect a multiple-point fault before it can contribute to a multiple-point failure [1]”.

NOTE 2: Multiple-Point faults with more than two elements are not considered in the analysis, except if it can be proven that they are relevant.

These different types of fault classifications are demonstrated in figure 3-4.

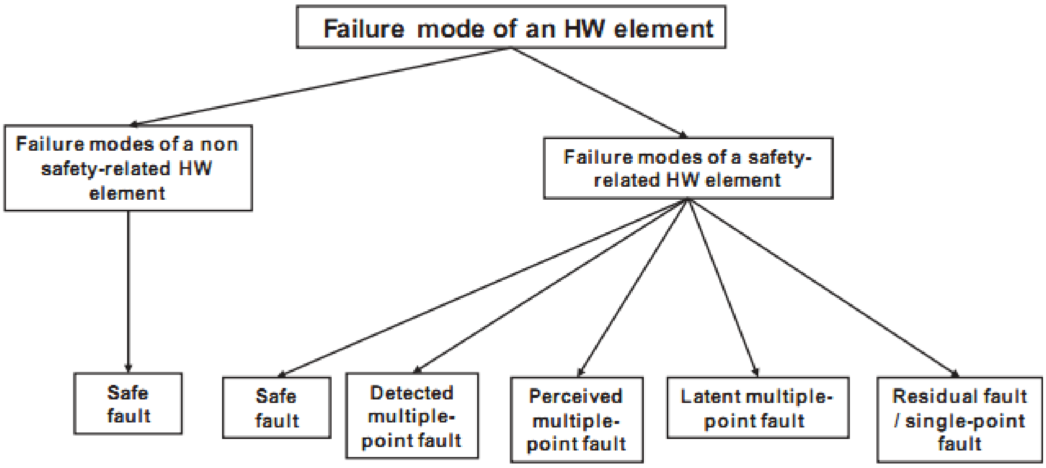

Failure mode of an HW element
Failure modes of a non safety-related HW element
Failure modes of a safety-related HW element
Safe fault
Safe fault
Detected multiple-point fault
Perceived multiple-point fault
Latent multiple-point fault
Residual fault / single-point fault

Figure 3-4: Failure Modes of an HW element

Knowing the different types of fault classifications, the user has to understand how to attribute them to a failure mode. Figure 3-5 is a very useful flow diagram, which points the user in the right direction for failure mode classification.

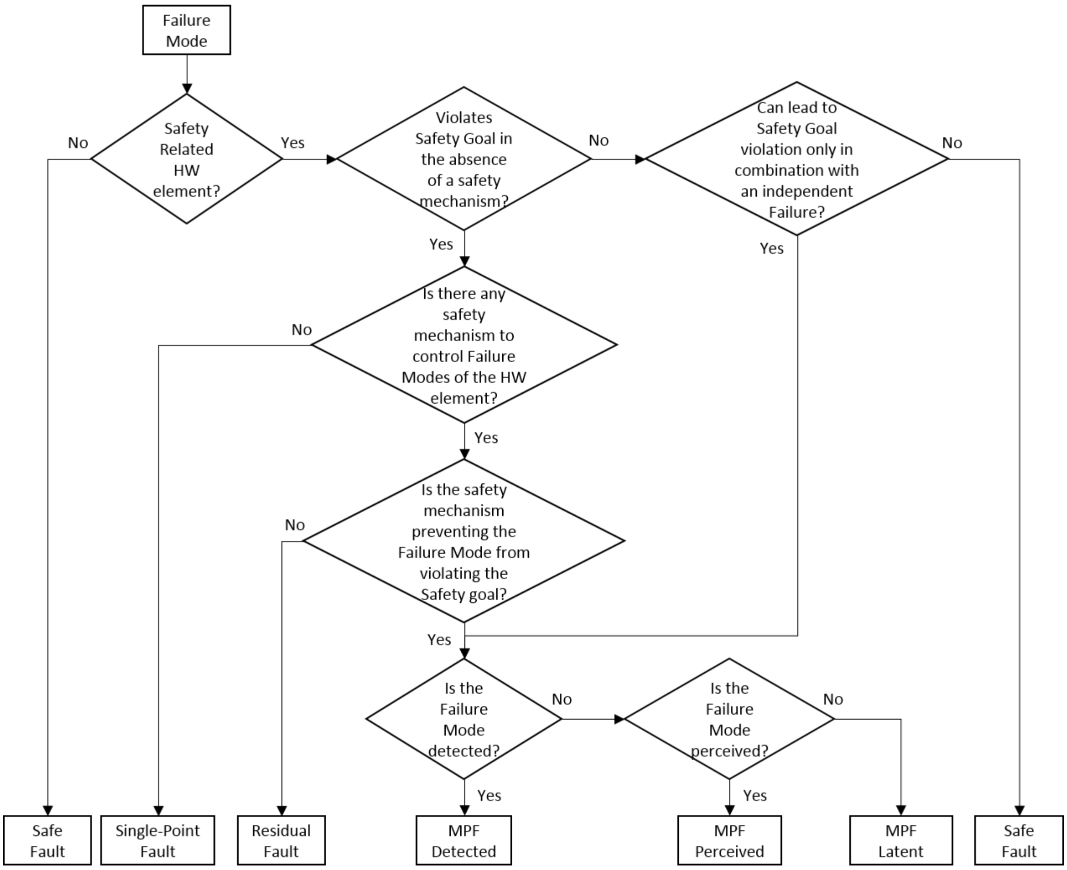

Failure Mode
Safety Related HW element?
No
Yes
Violates Safety Goal in the absence of a safety mechanism?
No
Can lead to Safety Goal violation only in combination with an independent Failure?
No
Yes
Yes
Is there any safety mechanism to control Failure Modes of the HW element?
No
Yes
Is the safety mechanism preventing the Failure Mode from violating the Safety goal?
No
Yes
Is the Failure Mode detected?
No
Is the Failure Mode perceived?
No
Yes
Yes
Safe Fault
Single-Point Fault
Residual Fault
MPF Detected
MPF Perceived
MPF Latent
Safe Fault

Figure 3-5: Flow diagram for failure mode classification [1]

3.4. ISO 26262 Hardware Metrics

As it has been said before, the 5th part of the ISO 26262 presents two metrics to evaluate the effectiveness of hardware architectures to cope with random hardware failures [1]. The results are then compared to target values, if those targets are not achieved, then the architecture must be improved by changing components or safety mechanisms. The hardware architectural metrics can be applied iteratively during the design phase and are dependent on the whole hardware of the item. [1]

There are also two other evaluations, that check the safety goal violations due to random hardware failures [1]. These are complementary to the metrics and are also going to be described.

To proceed with the metric evaluation, the designer has to estimate the failure rate of the components in the architecture that are relevant to the analysis. The estimated failure rate for the hardware parts of the item shall be determined:

a) Using hardware failure rate data from a recognized industry source (e.g.: IEC/TR 62380, IEC 61709, MIL HDBK 217 F notice 2,…), or [1]
b) Using statistics based on field tests. The estimated failure rate should have an adequate confidence level, or [1]
c) Using expert judgment founded on an engineering approach based on quantitative or qualitative arguments. A structured criteria should be the base for this judgment [1]

3.4.1 Architectural Metrics

There are two metrics described in ISO 26262, Single-Point Fault Metric and Latent Fault Metric. These evaluate the system's robustness, through the coverage from safety mechanisms. Higher metric values reflect safer systems, therefore low percentage of critical faults (single-point faults and residual/latent faults).

3.4.1.1. Calculating failure rates

It is also important to be aware of how the metric failure rates, single-point, residual and latent are calculated. The overall failure rate of the hardware element or component (safety-related) is:

$$\lambda = \lambda_{SPF} + \lambda_{RF} + \lambda_{MPF} + \lambda_{S}$$

$$\lambda_{SPF} \rightarrow total\ failure\ rate\ for\ single\ point\ faults\ in\ the\ component$$
$$\lambda_{RF} \rightarrow total\ failure\ rate\ for\ residual\ faults$$
$$\lambda_{MPF} \rightarrow total\ failure\ rate\ for\ multiple\ point\ faults$$
$$\lambda_{S} \rightarrow total\ failure\ rate\ for\ safe\ faults$$

Single-point faults are not covered by any safety mechanism, therefore, the failure rate for single-point faults (λ_{SPF}) in the component is, simply, the failure rate of the fault (failure rate of the component, multiplied by the failure mode distribution):

$$\lambda_{SPF} = \lambda$$

$$\lambda \rightarrow failure\ rate\ of\ the\ fault$$

The residual fault's failure rate ($\lambda_{RF(est)}$) is determined from the diagnostic coverage of the safety mechanisms. A single-point fault can be prevented, mitigated or eliminated by a safety mechanism and the hazard only happens if the mechanism fails. However, if the diagnostic coverage in not 100%, the fault can be a residual fault, then the estimated failure rate is:

$$\lambda_{RF(est)} = \lambda \times (1 - (K_{DC-RF}/100))$$

$$K_{DC-RF} \rightarrow diagnostic\ coverage\ percentage\ in\ residual\ faults$$
$$\lambda \rightarrow failure\ rate\ of\ the\ fault\ covered\ by\ the\ safety\ mechanism$$

The faults that lead directly to the violation of the safety goal, single-point faults or residual faults, cannot contribute anymore to the latent faults population [1].

λ_{MPF} is the sum of perceived or detected multiple point faults and latent faults. This breaking down introduces the concept of detectability using diagnostic coverage: some faults are perceived by the driver directly and some are detected by safety mechanisms. Latent faults are not detected.

Therefore, the failure rate of the latent failure mode ($\lambda_{MPF-L(est)}$) that is perceived by the driver or covered by a safety mechanism is the remaining failure rate of the residual fault, being covered by a safety mechanism, multiplied by the percentage of the estimated unperceived faults by the driver or uncovered faults by the safety mechanism:

$$\lambda_{MPF-L(est)} = (\lambda - \lambda_{RF(est)}) \times (1 - (K_{DC-MPF-L}/100))$$

$$K_{DC-MPF-L} \rightarrow estimated\ percentage\ of\ covered\ or\ perceived\ faults$$
$$\lambda \rightarrow failure\ rate\ of\ the\ fault\ covered\ by\ the\ safety\ mechanism$$
$$\lambda_{RF(est)} \rightarrow\ failure\ rate\ of\ the\ residual\ fault$$

However, a component can also be latent through degradation of its capabilities. The component still works, but if certain external conditions like electromagnetic interference or harsh atmospheric conditions occur, the component can fail. That is the combination of two basic events, despite the difficulty of expressing the external condition's failure rate, and according to the flow diagram for failure mode classification (Figure 3-5), this is a latent multiple-point failure. In ISO 26262 - part 5, annex E, examples of this type of MPFs are given. For the calculations of the metric, they don't consider the failure rate of the external event that triggers the fault, therefore, the failure rate for this kind of multiple point faults is just the failure rate of the failure mode:

$$\lambda_{MPF-L(est)} = \lambda$$

$$\lambda \rightarrow failure\ rate\ of\ the\ fault$$

3.4.1.2. Metrics

Now that the failure rates included in the hardware architectural metrics are explored, the values for the two metrics, single-point and latent, can be demonstrated.

The expression for the Single-Point Metric represents a relative contribution of the non-Single-Point/Residual faults to the combined failure rate of all the faults of the safety-related hardware elements that contribute to the hazard:

$$\lambda_{SPM} = 1 - \frac{\sum_{SR,HW}(\lambda_{SPF} + \lambda_{RF})}{\sum_{SR,HW}\lambda} = \frac{\sum_{SR,HW}(\lambda_{MPF} + \lambda_{S})}{\sum_{SR,HW}\lambda}$$

Figure 3-6 is a descriptive graph of the Single-Point Fault Metric calculation, which shows the faults included in it. It is the ratio of faults with order one against all the other faults that are considered in the contribution to the hazard.

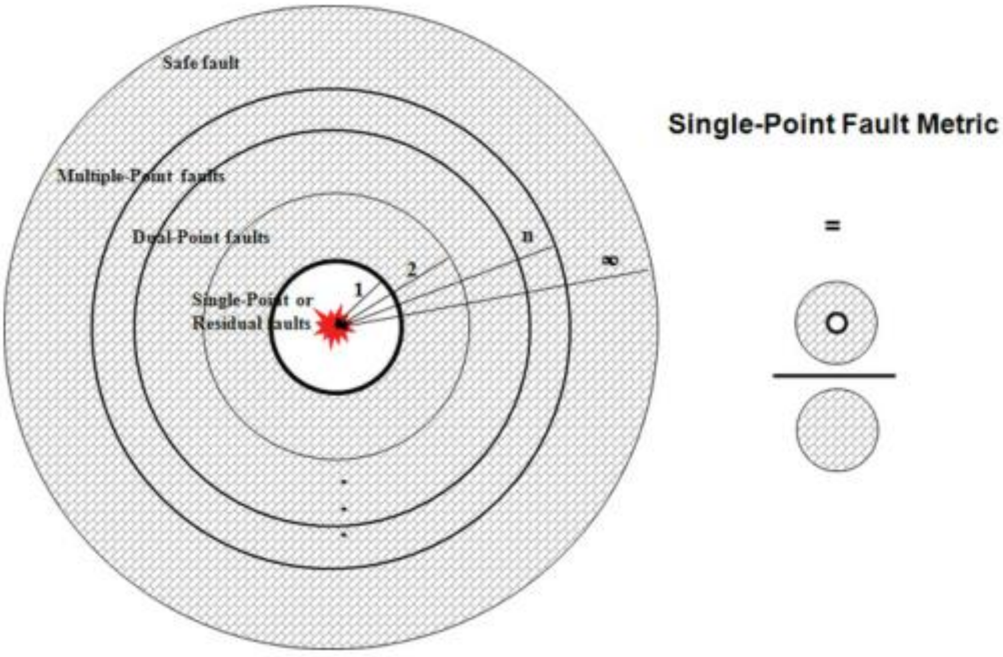


Figure 3-6: Single-Point Fault Metric [1]

As it has been said before, multiple-point faults with order 3 or higher can be ignored, unless proven to be important to the analysis. The Latent Fault Metric is a similar equation to the Single-Point Metric one. It is the ratio of the failure rates of non-Latent Multiple-Point faults (multiple-point perceived, detected or safe faults) against the total non-single-point/residual failure rates of the safety-related hardware elements that contribute to the hazard:

$$1-\frac{\sum_{SR,HW}(\lambda_{MPF-Latent})}{\sum_{SR,HW}(\lambda-\lambda_{SPF}-\lambda_{RF})}=\frac{\sum_{SR,HW}\left(\lambda_{MPF-perceived-or-detected}+\lambda_{S}\right)}{\sum_{SR,HW}(\lambda-\lambda_{SPF}-\lambda_{RF})}$$

Figure 3-7 is a descriptive graph of the Latent Fault Metric calculation, which shows the faults included in it. It is the ratio of faults with order 2 (or higher depending on their importance) that are not detected or perceived against all the other faults that are considered in the contribution to the hazard, except the ones already included in the Single-Point Metric calculation (single-point and residual).

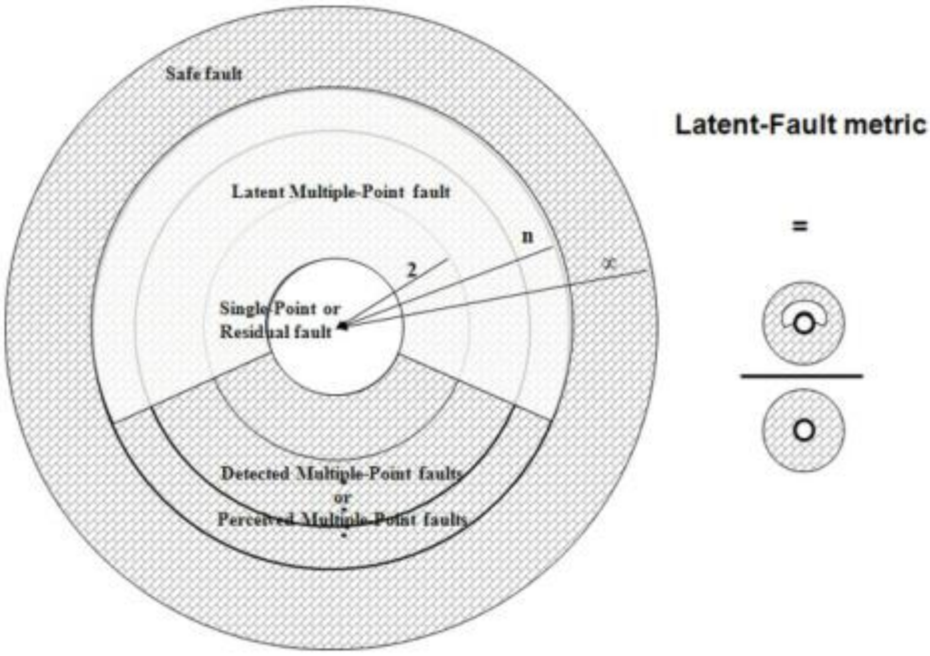

Safe fault
Latent-Fault metric
Latent Multiple-Point fault
n
2
∞
=
Single Point or
Residual fault
Detected Multiple-Point faults
or
Perceived Multiple-Point faults

Figure 3-7: Latent Fault Metric [1]

3.4.1.3. Target Values for the Metrics

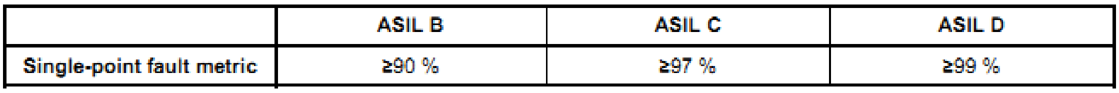
One of the objectives of the hardware architectural evaluation metrics is to compare hardware designs. After calculating the metrics for one design, these have to achieve certain target values.

ISO 26262 specifies, for each safety goal, a quantitative target value for the *Single-point fault metric* that shall be based on one of the following sources [1]:

a) Derived from hardware architectural metrics calculations applied on similar well trusted design principles, or

b) From Table 3.4

Table 3.4: Possible source for the derivation of the target “single-point fault metric” value [1]

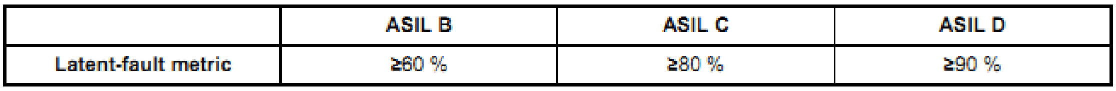


	ASIL B	ASIL C	ASIL D
Single-point fault metric	≥90 %	≥97 %	≥99 %

Similarly, the quantitative target value for the *Latent Fault metric* shall be based on one of the sources:

a) Derived from hardware architectural metrics calculations applied on similar well trusted design principles,
b) Derived from Table 3.5

Table 3.5: Possible source for the derivation of the target “latent-fault metric” value [1]



	ASIL B	ASIL C	ASIL D
Latent-fault metric	≥60 %	≥80 %	≥90 %

3.5. Evaluation of Safety Goal Violations

This is a complementary way of evaluating the reliability of a hardware architecture through the evaluation of safety goal violations due to random hardware failures.

To check if the Residual Risk of a safety goal violation (Random Hardware Failure) is sufficiently low, criteria for a rationale must be available. There are two ways to achieve this, both evaluate the residual risk of violating a safety goal due to Single-Point, residual and some Dual-Point faults [1]. The first method is called *Probabilistic Metric for random Hardware Failures* (PMHF) and the second is the individual evaluation of faults, which is a cut-set analysis.

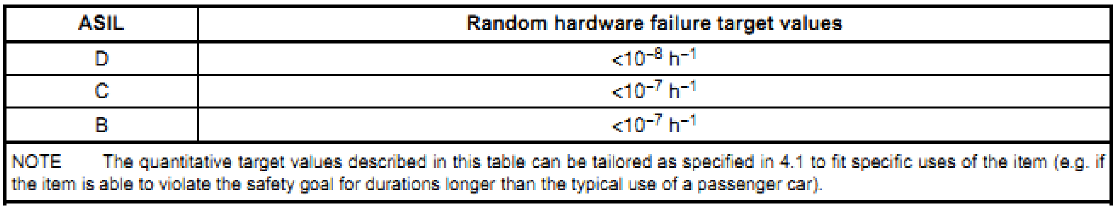
3.5.1. Probabilistic metric for Random Hardware Failures (PMHF)

The first method uses a *Probabilistic metric for Random Hardware Failures* (PMHF) and it uses, for example, quantified FTA to achieve a probabilistic top level result to be compared with a target value. Quantitative target values for the maximum probability of the violation of each safety goal shall be defined using: [1]

a) Field data from similar well-trusted design principles, or
b) Quantitative analysis techniques applied to similar well-trusted design principles, or
c) Table 3.6.

NOTE: these target values do not have absolute significance and are only used to compare a new design with existing ones. They are intended to make available design guidance and evidence that the design complies with the safety goals. [1]

Table 3.6: Possible source for the derivation of the random hardware failure target values



ASIL	Random hardware failure target values
D	$<10^{-8}\ h^{-1}$
C	$<10^{-7}\ h^{-1}$
B	$<10^{-7}\ h^{-1}$

NOTE The quantitative target values described in this table can be tailored as specified in 4.1 to fit specific uses of the item (e.g. if the item is able to violate the safety goal for durations longer than the typical use of a passenger car).

NOTE: The values in Table 3.6 are expressed in average probability per hour over the operational lifetime of the item. [1]

In the next chapter, there will be an example of how to use this method, using Fault Tree Analysis.

3.5.2. Individual evaluation

The second method is the individual evaluation of each residual and single-point fault and of each dual-point failure leading to the violation of the safety goal. It can be considered a cut-set analysis. [1]

This method is illustrated in the flowcharts below (figures 3-8 and 3-9), it will only be introduced and theoretically explained, as the PMHF method is more interesting to combine with the HiP-HOPS, despite HiP-HOPS being able to produce cut-sets.

3.5.2.1. Requirements for Individual Evaluation

The failure rate class ranking for a hardware part shall be determined as [1]:

a) The failure rate class 1 failure rate has to be less than the target for ASIL D divided by 100. If there is a rationale the dividing number can be lower than 100, then a correct ranking must be maintained while considering single-point, residual faults and higher degree cut-sets together.
b) Failure rate for the failure rate class 2 shall be less or equal to 10 times the failure rate in class 1.
c) Failure rate for the failure rate class 3 shall be less or equal to 100 times the failure rate in class 1.
d) The failure rate corresponding to failure rate class i, i > 3 shall be less than or equal to 10(i-1) times the failure rate corresponding to failure rate class 1.

An individual evaluation of each single-point, residual and dual-point failure violating the safety goal shall be performed at the hardware part level. Furthermore, evidence must be provided that the requirements introduced here are met. [1]

3.5.2.2. Individual evaluation for Single-Point and Residual Faults

Each Single-Point fault is evaluated using criteria on the occurrence of the fault, Residual Faults are evaluated using criteria combining the occurrence of the fault and the efficiency of the safety mechanism [1]. The evaluation procedure is stated in Figure 3-8.

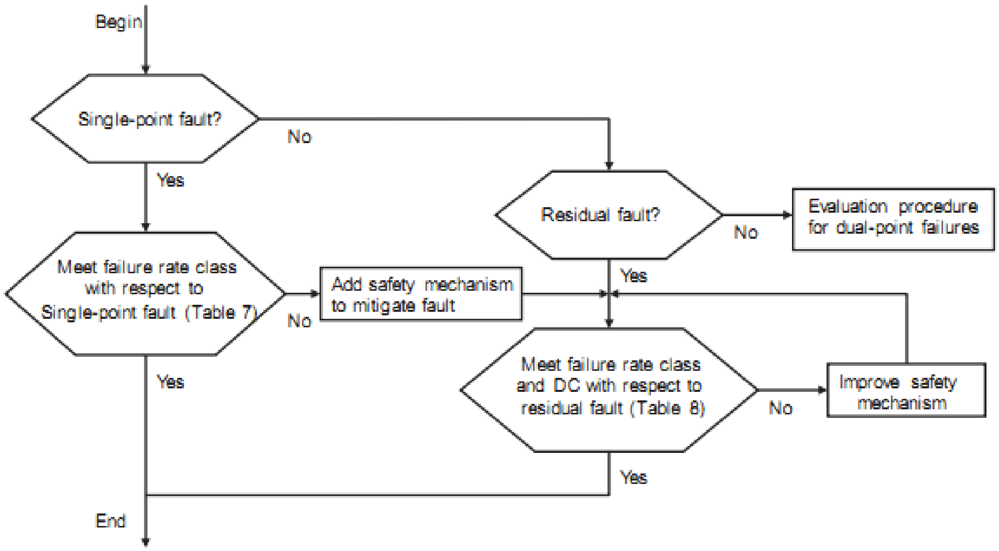

Begin
Single-point fault?
No
Yes
Residual fault?
No
Evaluation procedure for dual-point failures
Yes
Meet failure rate class with respect to Single-point fault (Table 7)
No
Add safety mechanism to mitigate fault
Meet failure rate class and DC with respect to residual fault (Table 8)
No
Improve safety mechanism
Yes
Yes
End

Figure 3-8: Evaluation procedure for single-point and residual faults [1]

The target values for each single-point fault and residual fault are expressed in Table 3.7 and 3.8, respectively.

A single-point fault can be considered acceptable if the failure rate of the corresponding hardware element complies with the targets in Table 3.7 [1].

A residual fault can be overlooked if the failure rate class ranking complies with the targets given in Table 3.8, for the diagnostic coverage of that hardware part [1].

Table 3.7: Targets of failure rate classes of hardware parts regarding single-point faults [1]

ASIL of the safety goal	Failure rate class
D	Failure rate class 1 + dedicated measures[a]
C	Failure rate class 2 + dedicated measures[a] or Failure rate class 1
B	Failure rate class 2 or Failure rate class 1

[a] The note in requirement 9.4.2.4 gives examples of dedicated measures.

Table 3.8: Maximum failure rate classes for a given diagnostic coverage of the hardware part - residual faults [1]

ASIL of the safety goal	Diagnostic coverage with respect to residual faults			
	≥99,9 %	≥99 %	≥90 %	<90 %
D	Failure rate class 4	Failure rate class 3	Failure rate class 2	Failure rate class 1 + dedicated measures[a]
C	Failure rate class 5	Failure rate class 4	Failure rate class 3	Failure rate class 2 + dedicated measures[a]
B	Failure rate class 5	Failure rate class 4	Failure rate class 3	Failure rate class 2

[a] The note in requirement 9.4.2.4 gives examples of dedicated measures.

The dedicated measures that appear in the tables above can include [1]:

a) Design features such as hardware part over design or physical separation (e.g. spacing of contacts on a printed circuit board);
b) Special sample test of incoming material to reduce risk of occurrence of this failure mode;
c) Burn-in test;
d) Dedicated control set as part of the control plan;
e) Assignment of safety-related special characteristics.

3.5.2.3. Individual Evaluation for Dual-Point Failures

Dual-Point failures are evaluated firstly by their plausibility. A Dual-Point failure is not plausible if both faults that lead to the failure are detected in a sufficiently short time with sufficient coverage. If it is plausible, then the faults causing it are evaluated using criteria combining occurrence of the fault with coverage of the safety mechanisms. This method is expressed by the flowchart below (Figure 3-9). [1]

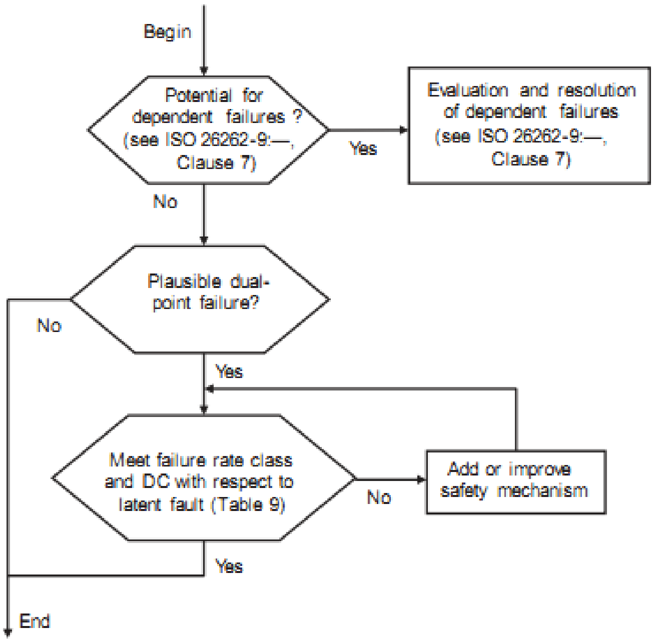

Begin
Potential for dependent failures ? (see ISO 26262-9:—, Clause 7)
Yes
Evaluation and resolution of dependent failures (see ISO 26262-9:—, Clause 7)
No
Plausible dual-point failure?
No
Yes
Meet failure rate class and DC with respect to latent fault (Table 9)
No
Add or improve safety mechanism
Yes
End

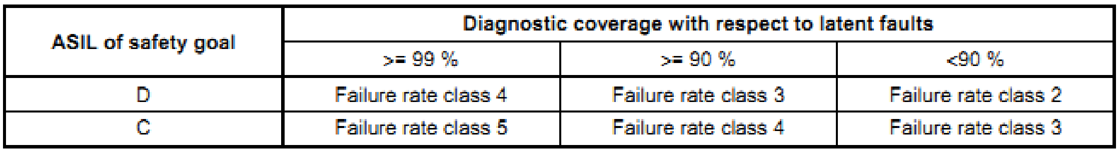
Figure 3-9: Evaluation procedure for dual-point failures [1]

A dual-point failure is plausible if [1]:

- ASIL D:
    - One or both the hardware parts have diagnostic coverage of less than 90%, or
    - One of the dual-point faults causing the dual-point failure remains latent for a time longer than the multiple-point detection interval
- ASIL C:
    - One or both the hardware parts have diagnostic coverage of less than 80%, or
    - One of the dual-point faults causing the dual-point failure remains latent for a time longer than the multiple-point detection interval

For ASIL D and ASIL C, a dual-point failure that is not plausible shall be considered compatible with the safety goal target and accepted. If it is plausible, can be considered acceptable if the hardware part complies with the failure rate targets for the failure rate class ranking and diagnostic coverage in Table 3.9. [1]

Table 3.9: Targets of failure rate class and coverage of hardware part regarding dual-point faults [1]



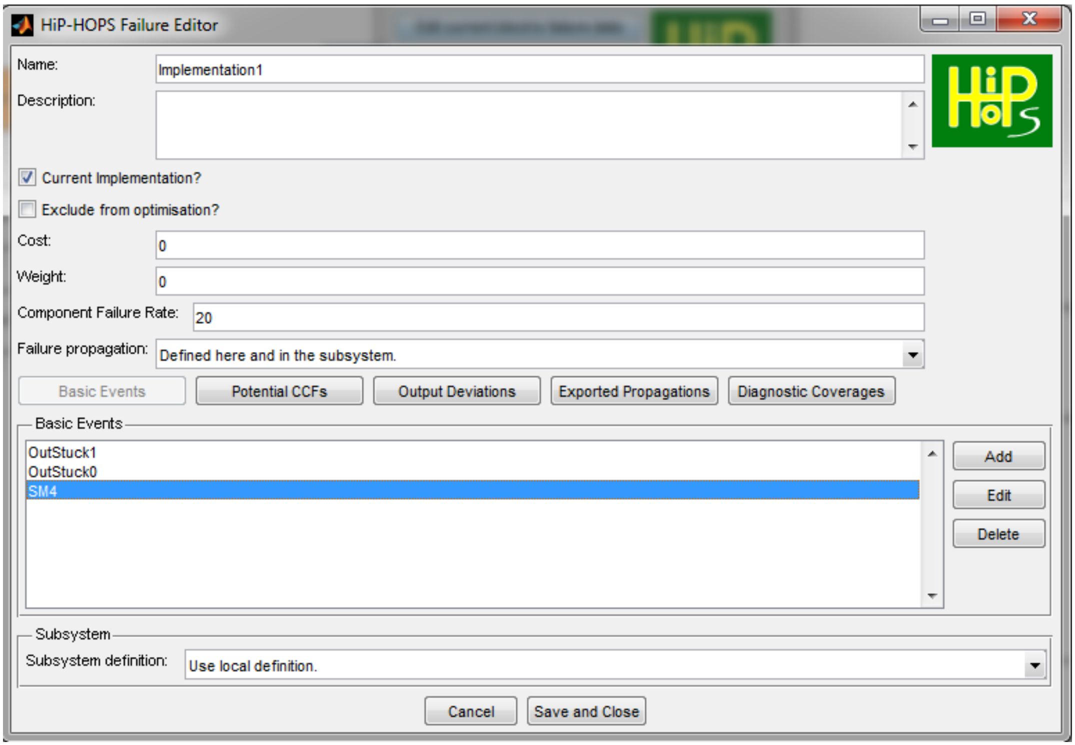
ASIL of safety goal	Diagnostic coverage with respect to latent faults		
	>= 99 %	>= 90 %	<90 %
D	Failure rate class 4	Failure rate class 3	Failure rate class 2
C	Failure rate class 5	Failure rate class 4	Failure rate class 3

3.6. Automatic Evaluation Techniques with HiP-HOPS

The main objective of this thesis is to implement changes in HiP-HOPS, so that it accommodates some of the concepts in ISO 26262 regarding hardware. It was decided that the most interesting concepts to the automotive industry were the hardware evaluation techniques. Now that those techniques have been introduced in this chapter, the question of how they can be implemented in HiP-HOPS arises.

3.6.1. Hardware Metrics

First, it was decided how the safety mechanisms should be implemented in the model. A safety mechanism can be an entire element or part of one, so it should have its own failure rate. Therefore it is a basic event, so if a hardware element is a safety mechanism or contains one then a basic events should be the failure of that safety mechanism, like in figure 3-10. The name of the basic event should start with “SM”.



Name: Implementation1

Description:

☑ Current Implementation?

☐ Exclude from optimisation?

Cost: 0

Weight: 0

Component Failure Rate: 20

Failure propagation: Defined here and in the subsystem.

Basic Events

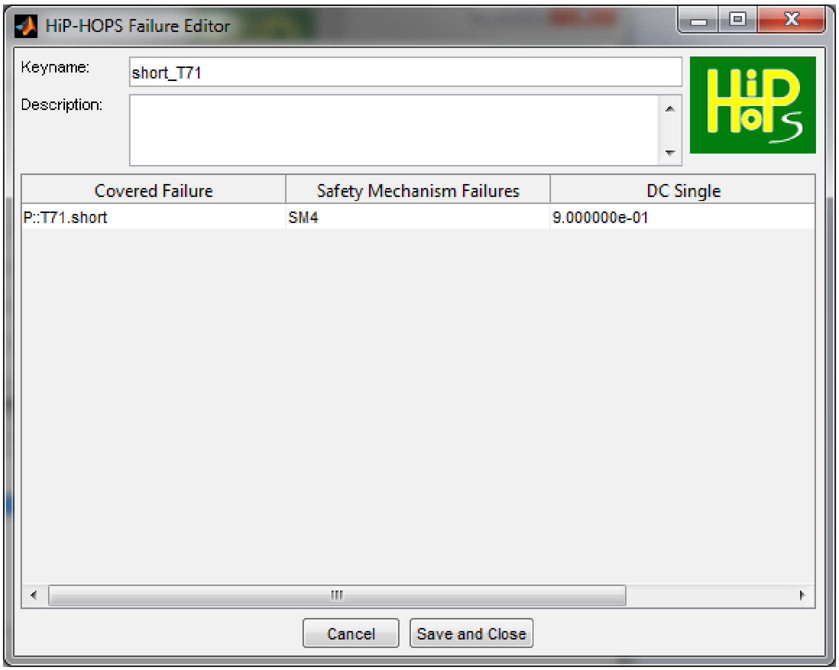
- OutStuck1
- OutStuck0
- SM4

Subsystem

Subsystem definition: Use local definition.

Figure 3-10: Safety Mechanism Element

It is also necessary to know the elements covered by the safety mechanism. For this reason and considering the element which is the safety mechanism in the Diagnostic Coverage tab, the user must input which failure modes of which elements are covered. Figure 3-11 is an example of that, where the failure mode “short” of the component “T71” is covered by the safety mechanism named “SM4”, with diagnostic coverage of 90% for single-point faults. There is also a column for the coverage of latent faults or for the estimated amount of perceived fault by the driver.



Keyname: short_T71

Description:

Covered Failure	Safety Mechanism Failures	DC Single
P::T71.short	SM4	9.000000e-01

Figure 3-11: Coverage of a component

NOTE: Covered Failure is the fully qualified name of the failure mode. In this case, “P::” means that the system is in fact a subsystem of the system “P”, “T71” is the component and “short” is the failure mode.

With this information in the model, the program knows which components are or contain safety mechanisms and the failure modes of the components covered by it.

In the next chapter the program developed to do the calculations automatically will be described.

3.6.2. Probabilistic metric for Random Hardware Failures (PMHF)

If the model holds all the necessary information, then it can be quite simple to perform this method, since the calculations are basic. HiP-HOPS performs Fault Tree Analysis automatically, but without safety mechanisms. So it is necessary to add safety mechanisms to the fault tree, with the respective failure rates and diagnostic coverage. In ISO 26262 - part 10 there is an example of the PMHF, which shows how to model the safety mechanisms and, therefore, residual faults in the fault tree.

Figure 3-12 is an example with safety mechanisms in the fault tree. Register R0 is covered by safety mechanism SM1, in its absence the R0 fault branch would just contain the failure rate of that element instead it has a new branch “R0 fault undetected”. This new branch is an OR with the possible combinations where the fault is not detected, “1-R0 diagnostic coverage” (the residual fault) OR “diagnostic coverage, but failure of the safety mechanism SM1”. Meanwhile, SM1 is also covered by another safety mechanism (SM2), therefore, the combination is a latent fault (failure of Register R0 and safety mechanism SM1). Figure 3-13 shows the possibilities of the failure of SM1. It is similar to the fault tree in figure 3-12, with the combinations of the failure of SM1 being the “failure rate of SM1” AND “no diagnostic coverage” (residual fault) OR “diagnostic coverage” AND “failure rate of SM1”. The last hypothesis is a special case, since SM2 only tests once in an hour, so despite SM2 being covering SM1, the safety mechanism SM1 can fail while SM2 is not testing.

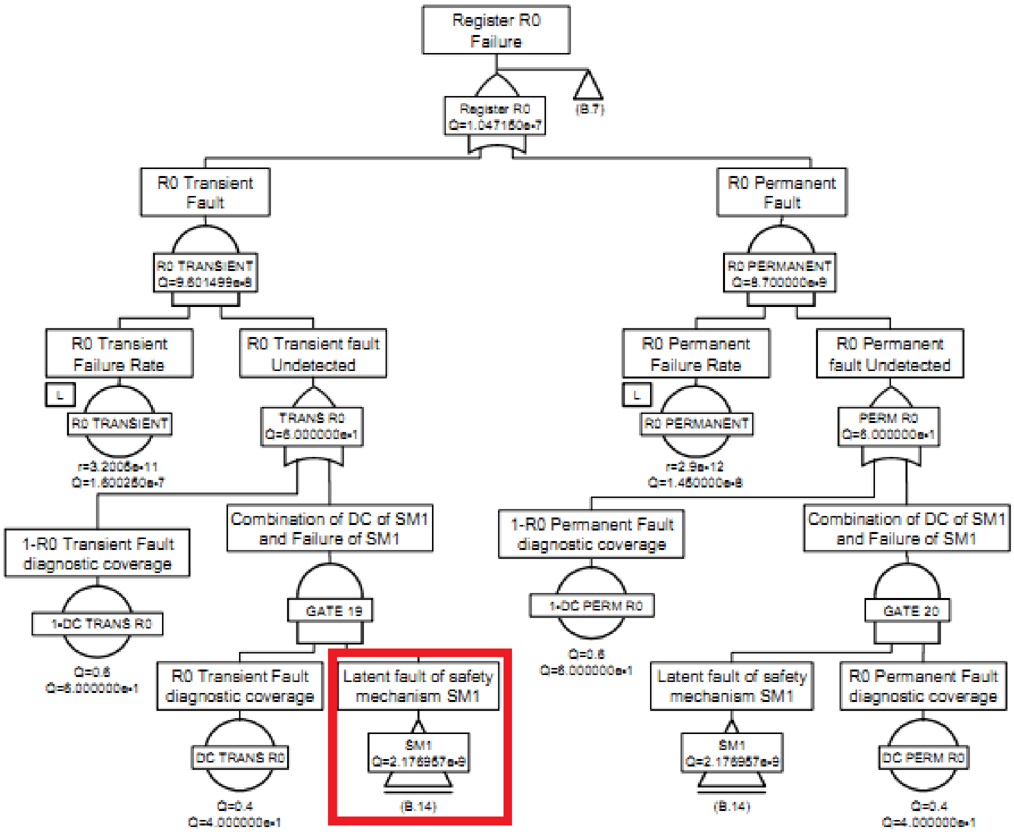

Register R0 Failure
Register R0 Q=1.047160e-7
(B.7)
R0 Transient Fault
R0 TRANSIENT Q=9.601499e-8
R0 Permanent Fault
R0 PERMANENT Q=8.700000e-9
R0 Transient Failure Rate
L
R0 TRANSIENT
r=3.2005e-11
Q=1.600260e-7
R0 Transient fault Undetected
TRANS R0 Q=6.000000e-1
R0 Permanent Failure Rate
L
R0 PERMANENT
r=2.9e-12
Q=1.450000e-8
R0 Permanent fault Undetected
PERM R0 Q=6.000000e-1
1-R0 Transient Fault diagnostic coverage
1-DC TRANS R0
Q=0.6
Q=6.000000e-1
Combination of DC of SM1 and Failure of SM1
GATE 19
1-R0 Permanent Fault diagnostic coverage
1-DC PERM R0
Q=0.6
Q=6.000000e-1
Combination of DC of SM1 and Failure of SM1
GATE 20
R0 Transient Fault diagnostic coverage
DC TRANS R0
Q=0.4
Q=4.000000e-1
Latent fault of safety mechanism SM1
SM1 Q=2.176957e-9
(B.14)
Latent fault of safety mechanism SM1
SM1 Q=2.176957e-9
(B.14)
R0 Permanent Fault diagnostic coverage
DC PERM R0
Q=0.4
Q=4.000000e-1

Figure 3-12: Fault tree of a covered element

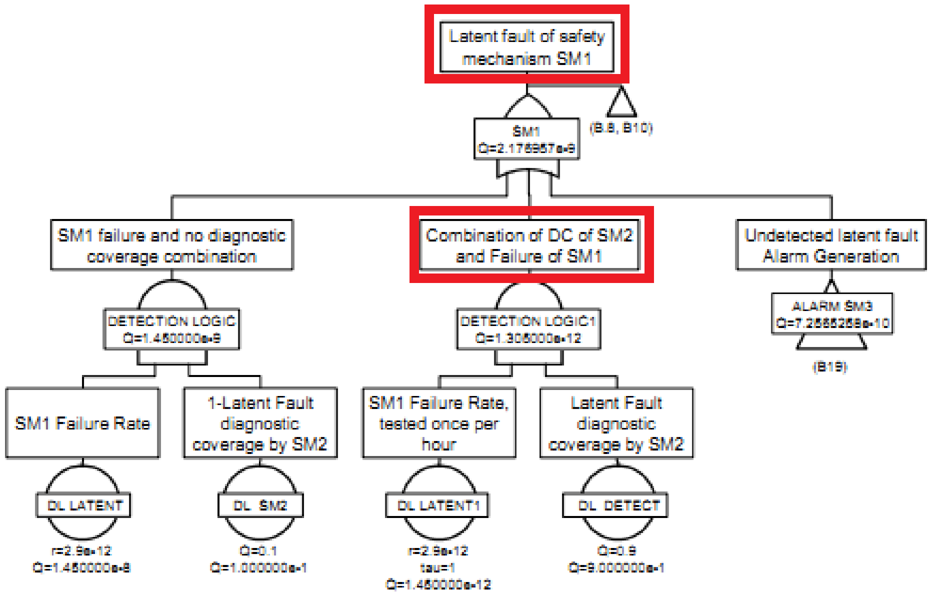

Latent fault of safety mechanism SM1
SM1 Q=2.176957e-9
(B.8, B10)
SM1 failure and no diagnostic coverage combination
DETECTION LOGIC Q=1.450000e-9
Combination of DC of SM2 and Failure of SM1
DETECTION LOGIC1 Q=1.305000e-12
Undetected latent fault Alarm Generation
ALARM SM3 Q=7.2585258e-10
(B19)
SM1 Failure Rate
DL LATENT
r=2.9e-12
Q=1.450000e-8
1-Latent Fault diagnostic coverage by SM2
DL SM2
Q=0.1
Q=1.000000e-1
SM1 Failure Rate, tested once per hour
DL LATENT1
r=2.9e-12
tau=1
Q=1.450000e-12
Latent Fault diagnostic coverage by SM2
DL DETECT
Q=0.9
Q=9.000000e-1

Figure 3-13: Fault tree for the failure of a covered safety mechanism

The general algorithm implemented in HiP-HOPS is to search every basic event of all the components, while the safety mechanisms and the component's failure modes that they cover, are previously known. If a searched component is covered by any safety mechanism, then its basic event is replaced by a new fault tree, in which the coverage of the safety mechanism is included. Figure 3-14 is an example of the fault tree that replaces the basic event. The event to be replaced is the latent fault of SM1 (it is latent because SM1 is covered by a safety mechanism SM4). It is replaced by the combination of "failure of SM1" AND "no diagnostic coverage" (residual fault) OR "failure of SM1" AND "failure of SM4".

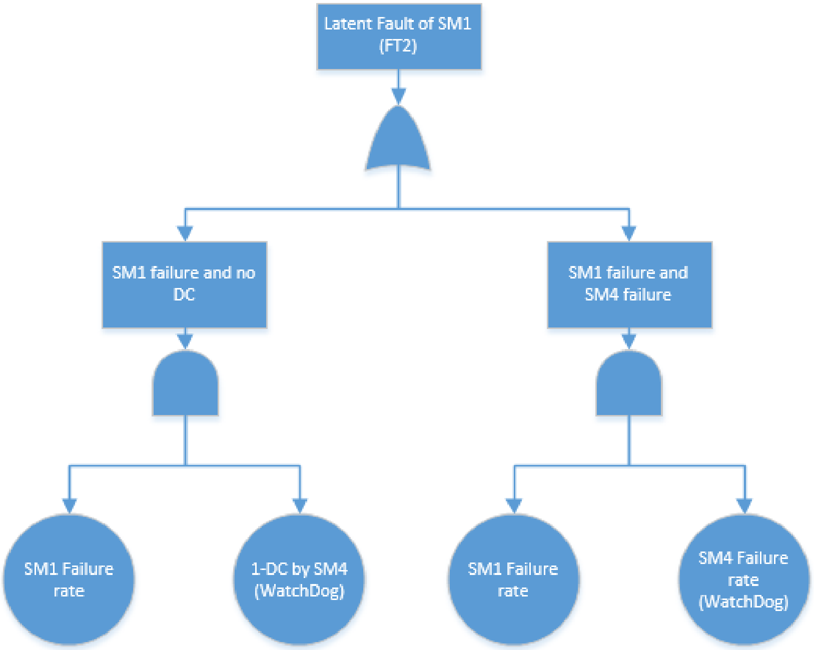

Latent Fault of SM1 (FT2)
SM1 failure and no DC
SM1 failure and SM4 failure
SM1 Failure rate
1-DC by SM4 (WatchDog)
SM1 Failure rate
SM4 Failure rate (WatchDog)

Figure 3-14: Fault tree that replaces the basic event of a covered component

3.7. Summary

Safety mechanisms were introduced in addition to ways to model them in system's models according to ISO 26262 rules. Fault Trees were also explained. This was one of the main objectives of this thesis. Furthermore, means for fault classification with safety mechanisms were given.

The other main goal of this thesis was to understand how the hardware architectural evaluation methods of ISO 26262 work. The two complementary metrics were explained and two methods to implement them in HiP-HOPS were proposed.

The next chapter contains the chosen hardware architecture to serve as an example for the program created for one metric and the changes made to fault tree analysis in HiP-HOPS to accommodate safety mechanisms.

Chapter 4

Implementation of the Hardware Evaluation techniques

This chapter serves as validation for the chosen approaches to add these ISO 26262 evaluation techniques to the state-of-the-art functional safety tool, HiP-HOPS.

4.1. ECU circuit example

ISO 26262 – part 5 contains an example for the first architectural evaluation metrics. It is a simple electronic circuit which has been chosen to validate the program that implements those metric calculations with HiP-HOPS, since it is possible to compare the results of that example with the results of the program.

4.1.1. Description of the system

The system has one function implemented on an ECU. The function has one input, the temperature measured through a sensor R3, and one output, a valve controlled by the component I71. The behavior of the function is to open the valve when the temperature is higher than 90 °C. That occurs if no current flows through I71 [1].

The safe state of the system is the open valve [1].

Associated with the function is the safety goal, assigned with ASIL B [1]:

"*valve* 2 *shall not be closed for longer than x ms when the temperature is higher than* 100 °C"

The value of the sensor R3 is read by one of the microcontroller’s ADCs. The resistance of R3 decreases as the temperature rises and there is not any safety mechanism monitoring that input. The output stage controls T71 and is monitored by the analogue input in the microcontroller InADC1, which is named SM1 (safety mechanism 1). It is assumed that the safety mechanism SM1 is able to detect some failure modes of the transistor T71, with a 90% diagnostic coverage in respect to the violation of the safety goal. If a failure is detected by the safety mechanism SM1, the safe state is activated. The diagnostic coverage of the latent faults is claimed to be 80% (the driver will notice the failure through the functionality degradation) [1].

NOTE 1: If no detailed information about the failure of complex elements is available, a conservative ratio of 50% safe faults can be assumed. It is also assumed that the microcontroller has a global coverage of 90% with respect to the violation of the safety goal, through internal self-tests and an external watchdog (safety mechanism SM4). The safety mechanism SM4 gets a signal from the output 0 of the microcontroller. If the watchdog is no longer refreshed, its output becomes low, goes into safe state and disconnects the microcontroller. If SM4 (watchdog and internal self-tests) detects any fault, it switches the function to the safe state and switches the LED L1 on. The claimed diagnostic coverage due to latent faults is 100 % because the LED L1 is switched on [1].

One of the problems noticeable in ISO 26262 is that it is not clear on some subjects. One of those subjects is the claimed diagnostic coverage of latent faults. In this example that diagnostic coverage is no more than the driver's perception and the value is claimed to be 80% for the function with no background explanation and 100% for the safety mechanism SM4, just because a LED is switched on.

The system for the function 1 can be seen in figure 4-1. It has a temperature sensor (R3) and a small acquisition circuit (C13, R23, R13 and C23), then the information is read by the ADC3 of the ECU (microcontroller) and outputted. The output controls the transistor T71, which controls the valve (I71 – valve control). The voltage controlled by the transistor T71 is covered by another acquisition circuit (C71, R73 and R74) that inputs that information to the ECU. Originally, the ISO 26262 example has another function with more electronic elements, but for the sake of validating the metric's results, function 1 is sufficient.

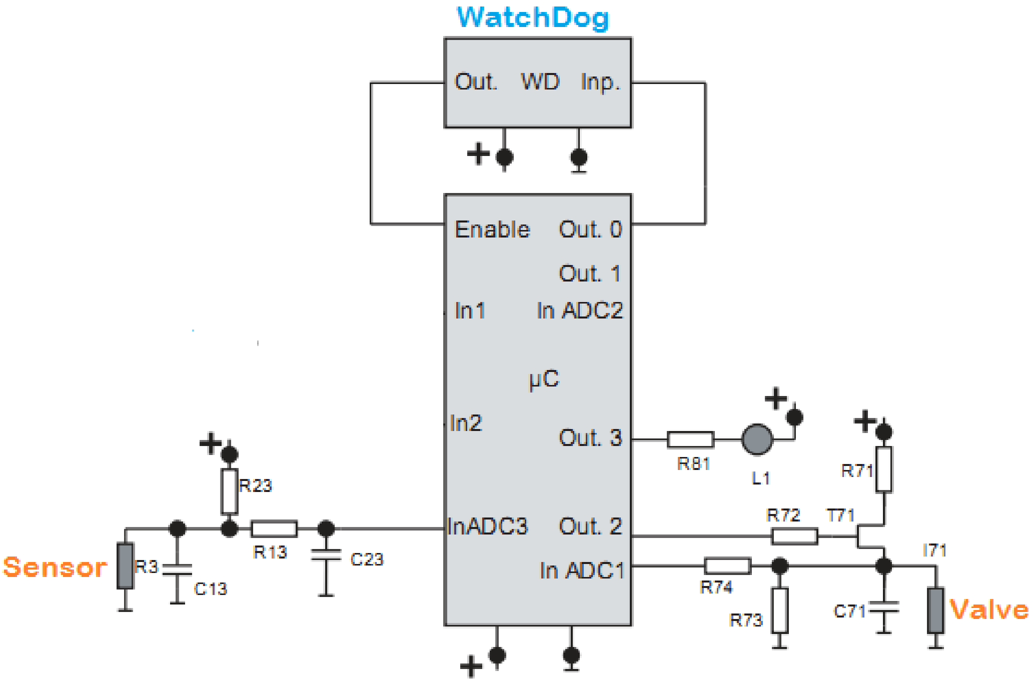
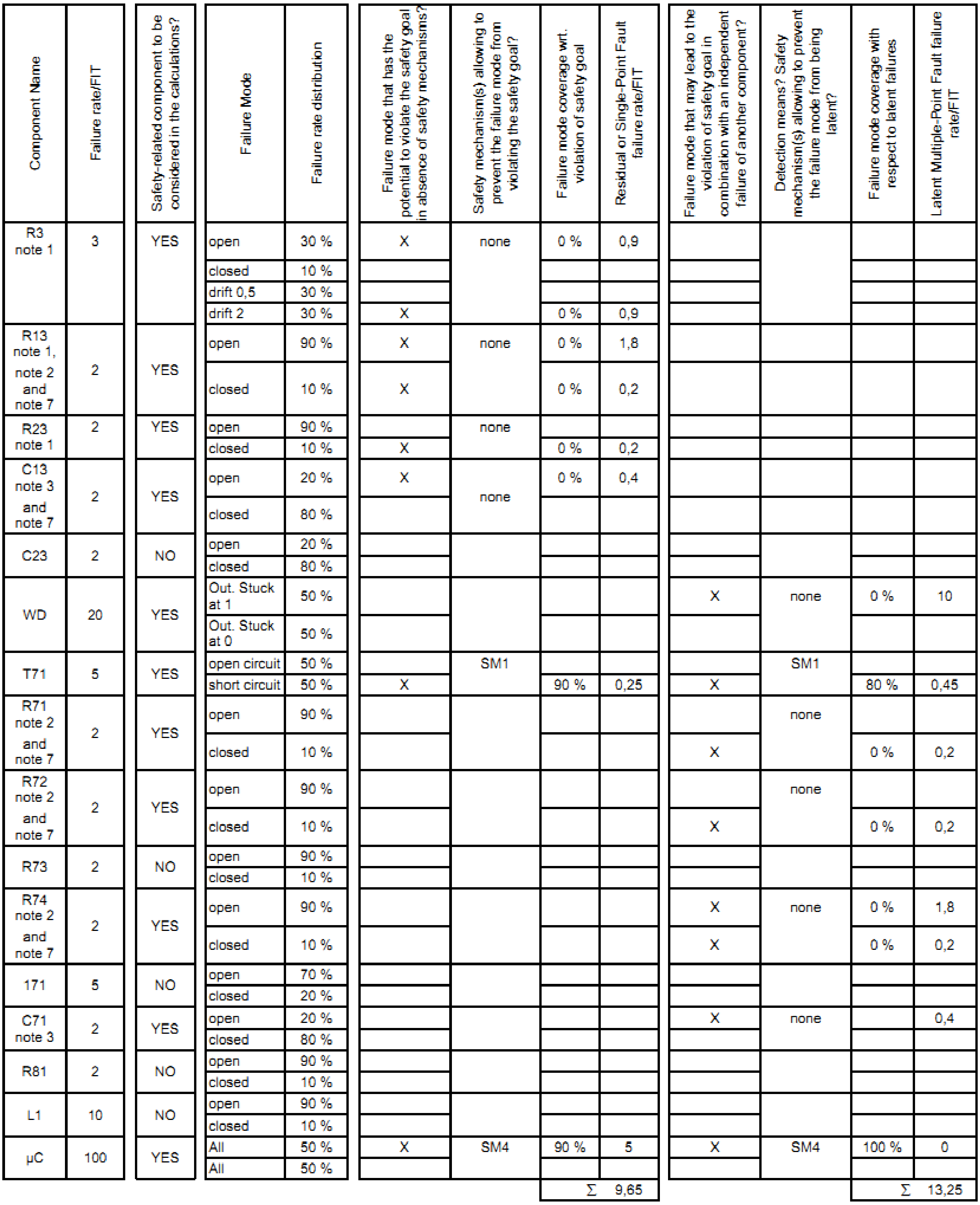


Figure 4-1: Function 1 electronic circuit

There is also a table (Table 4.1) describing the failure behavior of the components, the diagnostic coverage and other relevant information. The developed metric calculation program is able to reproduce a table like that in excel format, through the model information.

Table 4.1: Failure information for the system [1]



Component Name	Failure rate/FIT	Safety-related component to be considered in the calculations?	Failure Mode	Failure rate distribution	Failure mode that has the potential to violate the safety goal in absence of safety mechanisms?	Safety mechanism(s) allowing to prevent the failure mode from violating the safety goal?	Failure mode coverage wrt. violation of safety goal	Residual or Single-Point Fault failure rate/FIT	Failure mode that may lead to the violation of safety goal in combination with an independent failure of another component?	Detection means? Safety mechanism(s) allowing to prevent the failure mode from being latent?	Failure mode coverage with respect to latent failures	Latent Multiple-Point Fault failure rate/FIT
R3 note 1	3	YES	open	30 %	X	none	0 %	0,9				
			closed	10 %								
			drift 0,5	30 %								
			drift 2	30 %	X		0 %	0,9				
R13 note 1, note 2 and note 7	2	YES	open	90 %	X	none	0 %	1,8				
			closed	10 %	X		0 %	0,2				
R23 note 1	2	YES	open	90 %		none						
			closed	10 %	X		0 %	0,2				
C13 note 3 and note 7	2	YES	open	20 %	X	none	0 %	0,4				
			closed	80 %								
C23	2	NO	open	20 %								
			closed	80 %								
WD	20	YES	Out. Stuck at 1	50 %					X	none	0 %	10
			Out. Stuck at 0	50 %								
T71	5	YES	open circuit	50 %		SM1				SM1		
			short circuit	50 %	X		90 %	0,25	X		80 %	0,45
R71 note 2 and note 7	2	YES	open	90 %						none		
			closed	10 %					X		0 %	0,2
R72 note 2 and note 7	2	YES	open	90 %						none		
			closed	10 %					X		0 %	0,2
R73	2	NO	open	90 %								
			closed	10 %								
R74 note 2 and note 7	2	YES	open	90 %					X	none	0 %	1,8
			closed	10 %					X		0 %	0,2
171	5	NO	open	70 %								
			closed	20 %								
C71 note 3	2	YES	open	20 %					X	none		0,4
			closed	80 %								
R81	2	NO	open	90 %								
			closed	10 %								
L1	10	NO	open	90 %								
			closed	10 %								
µC	100	YES	All	50 %	X	SM4	90 %	5	X	SM4	100 %	0
			All	50 %								
							Σ	9,65			Σ	13,25

4.1.2. Failure Model

To work with HiP-HOPS it is necessary to model the system described above. It is not a functional model, but a failure propagation model, which contains information about the failure behavior of the components and the connections for the failure propagation. The model can be created with Matlab Simulink, Eclipse-based UML tools and ITI SimulationX. For this thesis Simulink is used due to previous experience with it. The created model can be seen in Figure 4-2. The model has got to have the proper physical connections to allow correct failure propagation, however it does not simulate the system's operation.

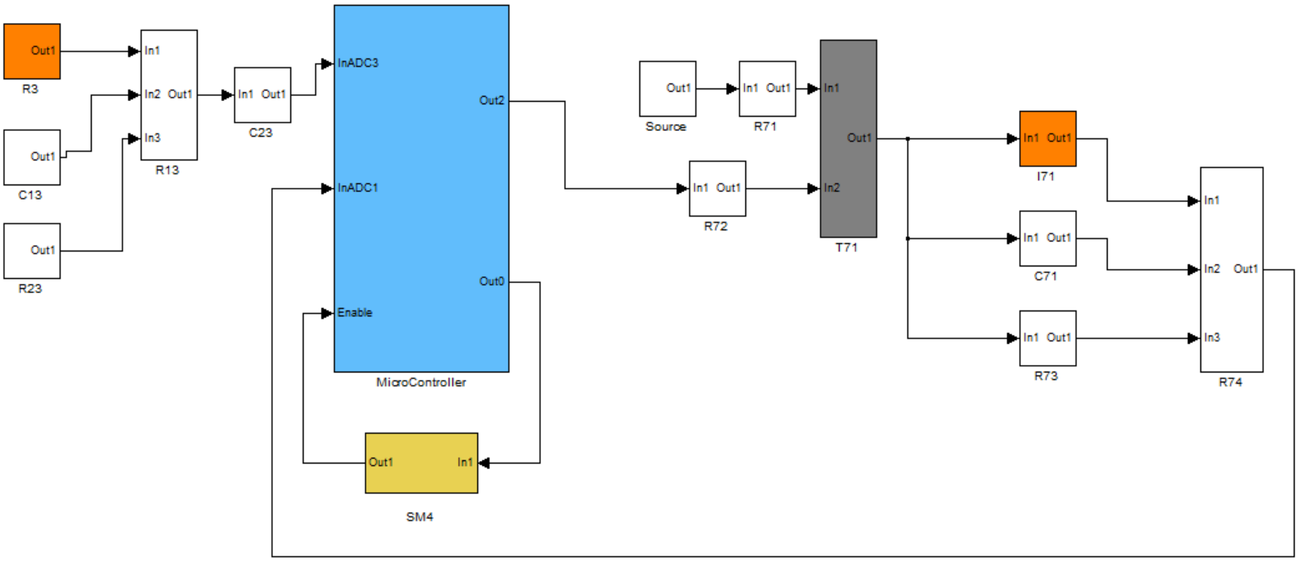


Figure 4-2: Failure Propagation Model

NOTE 1: The model is actually a sub-system inside an abstraction block named Perspective, which acts as the environment, to allow for external events (such as atmospheric conditions, electrical stress, etc.).

To understand how an electronic system can fail, the designer has to perform circuit analysis. This can be a difficult task for complex systems, however, this is not one of those and some information is already given in the ISO 26262 example. The only difficulty encountered while analyzing this system is the lack of information about the components, for example, in Table 4.1, they state that if R23 is in short circuit, then the safety goal is violated. It can be assumed that the safety goal is violated because the input value to the ECU is influenced, however that would depend on the value of the components that constitute the acquisition circuit.

4.2. System Failures Annotation

In this section, the system output is identified as well as the hazard associated with it. Also the failure behavior of the system's components is described and annotated.

4.2.1. System Function Failures and ASILs

First of all it is necessary to determine the hazards of the system. In this case, the hazard can be derived from the safety goal and its ASIL is specified in the ISO 26262 example, that information is described in Table 4.2.

Table 4.2: Model Function Failures and assigned ASILs

Function Failure (Hazard)	ASIL
Valve closed more than x ms when T > 90 ºC	B (2)

NOTE: The ASIL was assigned arbitrarily. If this was a real situation, a risk assessment procedure should take place. ISO 26262 gives guidelines of this procedures for automotive systems.

Function failures have to be associated with deviation of system's outputs in HiP-HOPS. The output of this system is the signal that I71 produces to control the electro mechanic valve.

This kind of annotation for the system output and all the other components will take place in this chapter. They will abide by the HiP-HOPS terminology rules, which have already been introduced in 2.6.2.1, in the following manner:

- Internal Failures:
    - "X-failureY". "X is replaced by the kind of deviation, "O" for Omission and "V" for value, for example. "Y" is the identifier of the failure, in the case that more than one failure of that type exist, or;
    - "Failure": which can be, for example, "short".
- Input and Output deviations: "X-name of input/output". "X" is replaced by the initial letter of the type of input/output deviation, like "O" for Omission.

The function failure is associated with the output deviations of the component I71. With the terminology rules in mind, the failure expressions of those output deviations are presented in table 4.3.

Table 4.3: Fault annotations - I71

Output Deviation	Causes
C-I71.Out1	C-In1

NOTE: I71.Out1 is the fully qualified name

4.2.2. System Fault and Safety Mechanism Annotations

Most of the components in this system are simple resistors, but some others like the temperature sensor or the valve can have several implementations. These failure annotations do not take into account any specific internal architecture of the components, however, it is possible to make assumptions regarding the way some components influence inputs failures to outputs.

NOTE: The fault model used for a given electronic part can differ depending on the application [1].

Example for the NOTE: The fault model of a resistor depends if the hardware part is used in a digital input (such as R11, R12, R13, etc.) or an analogue input (such as R3). In the first case the fault model can be "open/closed" whereas in the second case it can be "open/closed/drift" [1].

4.2.2.1. Temperature Sensor (R3)

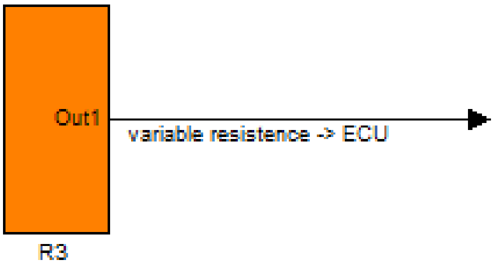


Figure 4-3: System Model - Temperature Sensor

This sensor in Figure 4-3 is a variable resistor, which changes its value with different temperatures. According to ISO 26262, this component has two behaviors that can lead to the violation of the safety goal. The failure mode "open" which leads to no signal and "drift 2" that leads to a different signal than the expected one. Table 4.4 presents the output deviation for it.

Table 4.4: Fault Annotations – Temperature Sensor

Output Deviation	Causes
V-Out1	drift2
O-Out1	open

4.2.2.2. Signal Acquisition Circuit

This circuit exists to formulate a desirable range for the input signal (depending on the temperature sensor internal architecture) to be correctly associated with a temperature value in the ECU. The circuit is presented in Figure 4-4 and the failure annotations of its components will be presented in the next tables.

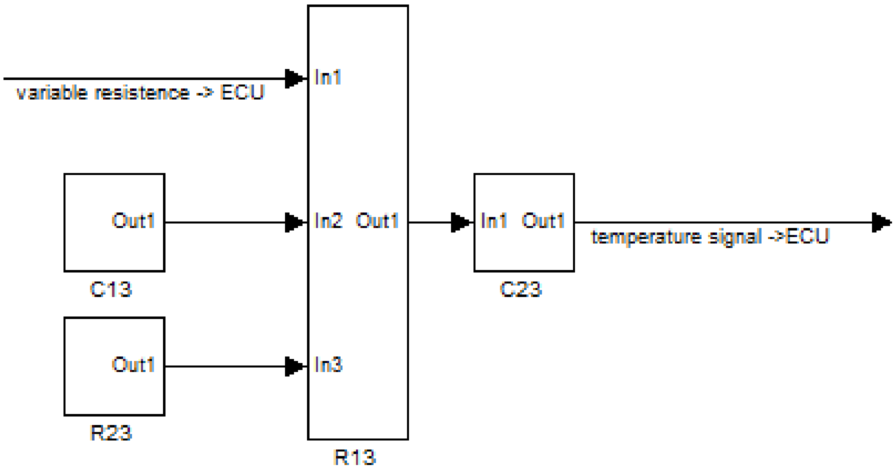


Figure 4-4: System Model – Signal Acquisition Circuit

Table 4.5: Failure Annotations – C13

Output Deviation	Causes
V-Out1	open

The purpose of the capacitor C13 is ESD protection. The failure mode open circuit means loss of protection [1].

NOTE 1: The classification of the failure modes leading to the loss of ESD or electrical protection is based on a case-by-case analysis and takes into consideration the likelihood of ESD or electrical stress and its characterized effects with respect to safety goal violation. If, for example, an ESD event is likely to occur during the vehicle lifetime and its effects can lead to the violation of the safety goal in absence of protection, then the failure mode leading to the loss of protection is considered a single-point fault [1].

NOTE 2: For all the failure modes that lead to the loss of electrical or ESD protection, I chose the deviation of the type value, just as a form of consistently annotating these types of failures.

Table 4.6: Failure Annotations – R23

Output Deviation	Causes
V-Out1	closed

For the resistor R23 (Table 4.6), the failure mode short circuit (closed), causes the direct violation of the safety goal, because it can change the value of the signal.

Table 4.7: Failure Annotations – R13

Output Deviation	Causes
V-Out1	closed
O-Out1	open

For the resistor R13, both failure modes, open and short circuit, lead to the violation of the safety goal. The failure mode short circuit (closed) means loss of electrical protection and is considered a single-point of failure. The failure mode open circuit, means that no signal reaches the ECU ADC.

The failure of the component C23 does not cause any danger towards the violation of the safety goal. It filters the sign and does not affect its value.

4.2.2.3. Microcontroller and WatchDog

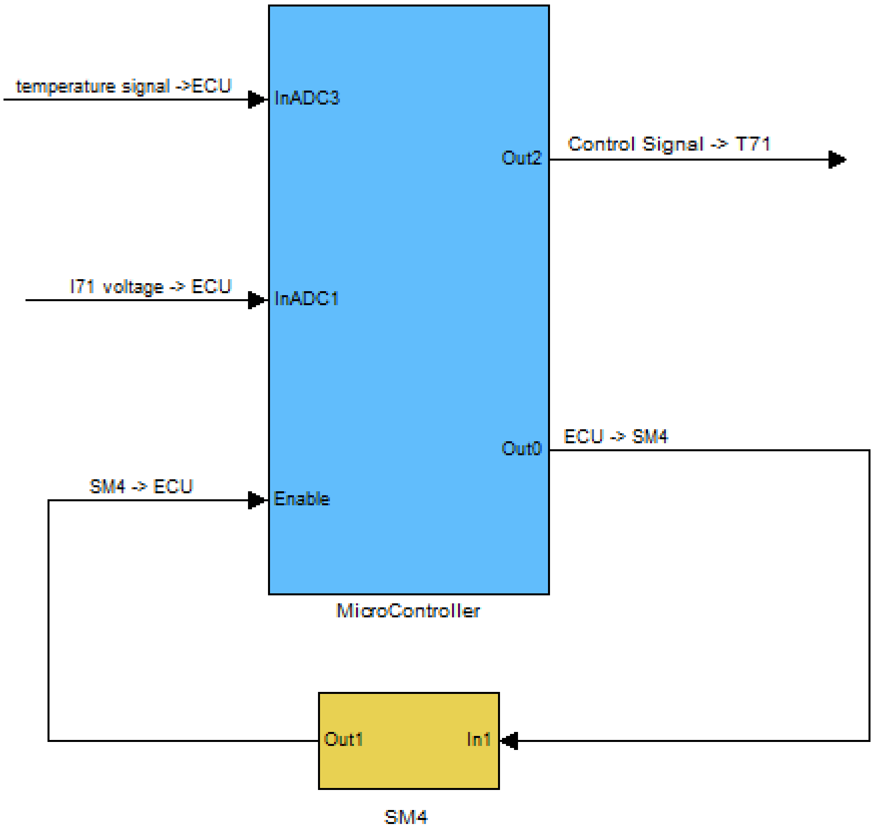


Figure 4-5: System Model – Microcontroller and WatchDog

The microcontroller, a complex component, normally named ECU in automotive electronics, analyses the signal of the variable resistor (R3), treated by the acquisition circuit and converted by the ADC1. From that digital signal, computes a temperature and controls the transistor T71 to close or open the valve, depending on the value of the temperature. Note 1 in 4.1.1 dictates that when there is no detailed information about a complex element, like this microcontroller, a ratio of 50% safe faults is assumed. This microcontroller has the safety mechanism SM4 covering its failure. It is a combination of an external WatchDog with internal self-tests, but, for the sake of simplifying the analysis, only the WatchDog will be considered.

The failure mode Output stuck at 1 of the safety mechanism SM4 (WD) contributes to the violation of the safety goal, but only in combination of harsh extreme conditions, that is why in Table 4.1 it is considered a Latent Fault (see NOTE 1). The safety mechanism covers the microcontroller with 90% of diagnostic coverage for the single-point fault and 100% for latent fault, because a LED is turned on, for the driver to notice the fault.

The diagnostic coverage annotations are in the WatchDog and can be seen in Table 4.9.

NOTE 1: The failure behavior that applies to the watchdog (SM4), also applies to the resistors R71, R72 and R74 and the capacitor C71. The failure modes can lead to the loss of electrical or ESD protection or other constricts, but the same thought process of violation of the safety goal only in combination with harsh external conditions applies.

Table 4.8: Failure Annotations - Microcontroller

Output Deviation	Causes
C-Out1	all

In Table 4.9, the output deviation of the microcontroller (μC) is commission, because the μC acts (signal output) correctly or not, depending on the information it receives (combination of temperature signal and I71 voltage).

Table 4.9: Diagnostic Coverage - Microcontroller

Covered Failure	Safety Mechanism	DC - Single	DC - Latent
P::Microcontroller.all	SM4 (WD)	90%	100%

Table 4.10: Failure Annotations - WatchDog

Output Deviation	Causes
C-Out1	Output stuck at 1 AND external

4.2.2.4. Actuation circuit

The purpose of this circuit is to open or close the valve, depending on the signal that the microcontroller outputs. T71 is transistor controlled by the μC which outputs a controlled voltage to the valve driver I71. R71 is a resistor connected to the source that feeds the actuator.

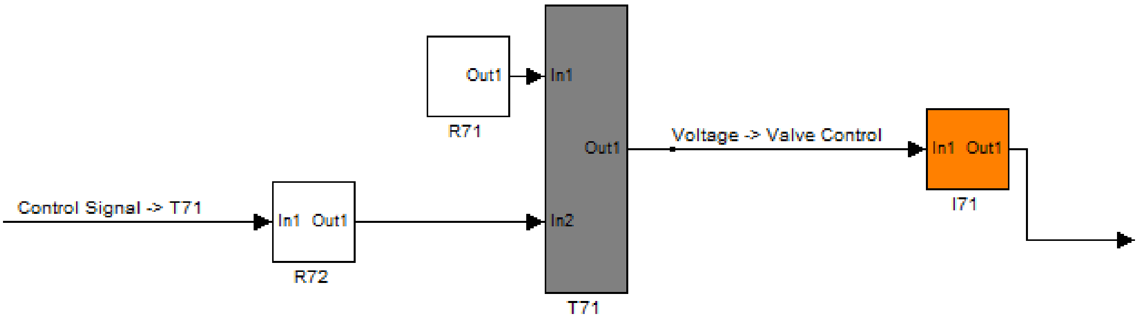


Figure 4-6: System Model - Actuation circuit

Table 4.11: Failure Annotations - Transistor T71

Output Deviation	Causes
C-Out1	short

If the transistor T71 is in short circuit, that is a direct violation of the safety goal, as the valve remains closed, no matter the temperature information or the control signal from the microcontroller. However, the voltage output of T71 is covered by the safety mechanism SM1, with diagnostic coverage of 90% in relation to the single-point fault (short circuit). If a failure is detected, then the safe state, valve open, is activated. In respect to what ISO 26262 names latent fault (because it enters in the latent fault metric) of this component (it is actually the estimated perceived fault by the driver), the diagnostic coverage of the driver is said to be 80%, because he can only notice the fault through functionality degradation. The annotations regarding the safety mechanism SM1 are done in the microcontroller, which is, in fact, that safety mechanism. That information is presented in Table 4.12.

NOTE 1: Despite ISO's 26262 example not having any information regarding how the safety mechanism SM1 actuation is actually implemented, we assume that there should be an additional transistor that can bypass the transistor T71 and control the valve driver (I71) on its own.

Table 4.12: Diagnostic Coverage - T71

Covered Failure	Safety Mechanism	DC - Single	DC - Latent
P::T71.short	SM1 (µC)	90%	80%

NOTE 2: P::T71.short is the fully qualified name of the basic event short in the component T71.

Table 4.13: Failure Annotations - R72

Output Deviation	Causes
C-Out1	closed and external

The resistor R72 has two possible failure modes, open or short circuit, however, the open circuit of this component does not contribute to the violation of the safety goal, since the valve will be open (safe state) because the transistor remains open. If the component is in short circuit, that leads to the loss of electrical protection. The safety goal is violated if that failure mode occurs and harsh external conditions apply, hence the reason why in Table 4.1, this is a latent failure (see NOTE 1 in 4.2.2.3).

Table 4.14: Failure Annotations - R71

Output Deviation	Causes
C-Out1	closed and external

If the component I71 (valve driver) fails, that has no effect regarding the violation of the safety goal, as the valve will remain in its safe state, open.

4.2.2.5. Signal Acquisition Circuit 2 - Safety Mechanism SM1

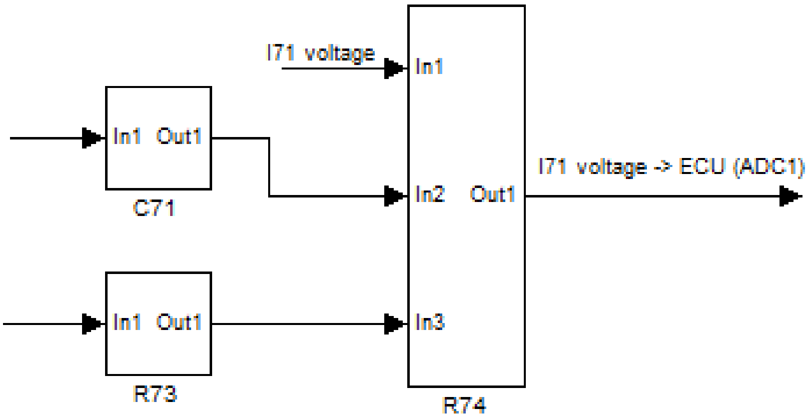


Figure 4-7: System Model - Signal Acquisition Circuit 2 (SM1)

This acquisition circuit is to modulate the voltage in I71 to be inputted by the ADC1 in the microcontroller. The failure annotations for its components are going to be presented in the next few tables.

The resistor R73 has no effect regarding the safety goal violation as it is merely a component to perform tension division.

Table 4.15: Failure Annotations – C71

Output Deviation	Causes
C-Out1	open and external

The failure mode open circuit of this component, means loss of ESD protection. That failure dictates that the component stays latent. It violates the safety goal if it is latent and certain external conditions happen.

Table 4.16: Failure Annotations – R74

Output Deviation	Causes
V-Out1	closed and external
O-Out1	open and external

The failure mode short circuit (closed) means loss of electrical protection, that fault in combination with certain external conditions leads to the violation of the safety goal. The other mode, open circuit also leads to the violation of the safety goal in combination with external conditions. This last failure mode contributes to an omission type of output deviation, as no value reaches the microcontroller's ADC.

IMPORTANT NOTE: Certain components need to have, as causes of output deviation, the inputs. That allows failure propagation.

Example of NOTE: The valve controller I71 needs to propagate the failures of the components that are behind it, to its output (system output). So its causes of output deviation, for the purposes of failure propagation, are the ones presented in Table 4.17.

Table 4.17: Failure Propagation Example – I71

Output Deviation	Causes
C-Out1	C-In1

4.3. Safety Analysis

Now that the electronic system has a model that is annotated with failure information, it is possible to perform safety analysis. This is not a complex system, so the analysis can be done manually. In Annex A.1 and A.2, the fault trees for this system are presented and will be explained in this section.

4.3.1. Fault Trees

Fault tree 1 (FT1) has as top event the hazard ("valve closed more than x ms when temperature is higher than 90 °C") and connected to it, below, an OR port that dictates all the possibilities that lead to the safety goal violation. For the purpose of this thesis faults were divided into three different main sections. First, the single-point failures, then the branches for failures that are covered by safety mechanisms and finally the failures of components that lead to the hazard in combination with other events.

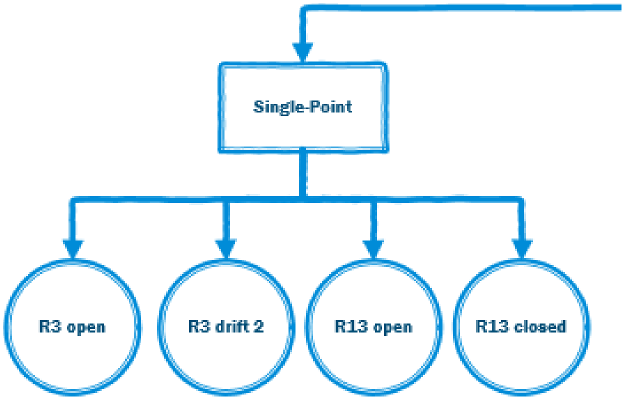


Figure 4-8: Fault Tree - Single-Point Failures

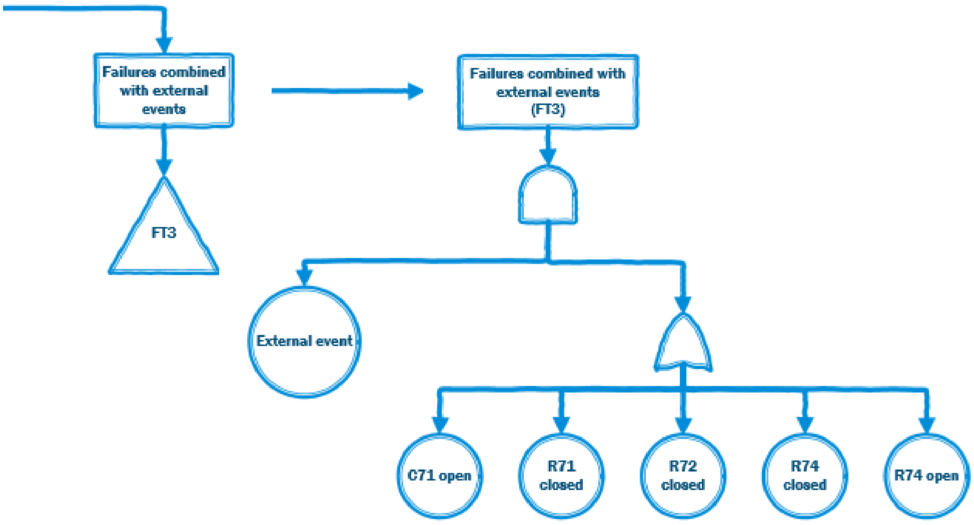

Failures combined with external events
FT3
Failures combined with external events (FT3)
External event
C71 open
R71 closed
R72 closed
R74 closed
R74 open

Figure 4-9: Fault Tree – Combination of Failures (Multiple-Point)

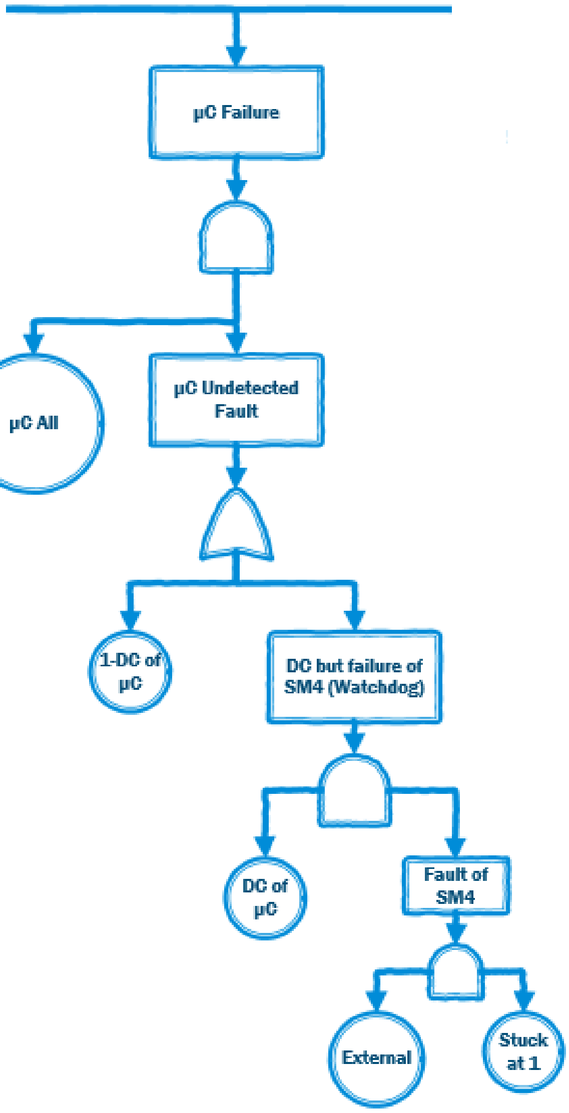


Figure 4-10: Fault Tree - Covered Failure

Figure 4-10 represents a new addition to the fault tree synthesis of HiP-HOPS, as it did not have safety mechanisms before. This branch is the failure of the microcontroller that is being covered by the safety mechanism SM4. There is another similar branch representing the failure of the transistor T71, covered by the safety mechanism SM1.

4.3.2. Using the Probabilistic metric for Random Hardware Failures (PMHF)

To serve as an example, the probability of failure of the microcontroller can be calculated, however it wasn't implemented in the HiP-HOPS code, yet:

$$FR\mu C * [(1 - dcSingle) + \left(dcSingle * (FR_{SM4} * P_{EXTERNAL})\right) = 27{,}5\ FIT$$

$$FIT - Failure\ in\ time$$
$$FR\mu C - Failure\ rate\ of\ the\ failure\ mode\ "all"\ in\ the\ microcontroller$$

$FR_{SM4} - Failure\ rate\ of\ the\ failure\ mode$ stuck at 1" $in\ the\ WatchDog$
$dcSingle - Diagnostic\ Coverage\ of\ the\ WatchDog\ for\ Single - Point\ Failures\ in\ the\ \mu C$
$P_{EXTERNAL} - Probability\ of\ harsh\ external\ conditions$

NOTE 1: The probability of harsh external conditions was considered to be 5%. This value has no theoretical fundament and was used merely to demonstrate.

NOTE 2: The Failure Rates given in the example of ISO 26262 – part 5 are not representative of a real case (too high), it is merely for demonstrative purposes.

NOTE 3: The branches for covered failures were done with the indications given in ISO 26262 – part 10, annex B (see Figures 3-12 and 3-13 in 3.6.2).

4.3.3. Cut-Sets

With the synthesis of the Fault Trees for the system hazard, it is possible to extract the minimal set of basic events that can violate the safety goal. Table 4.18 presents 16 cut-sets, of basic events capable of violating the safety goal.

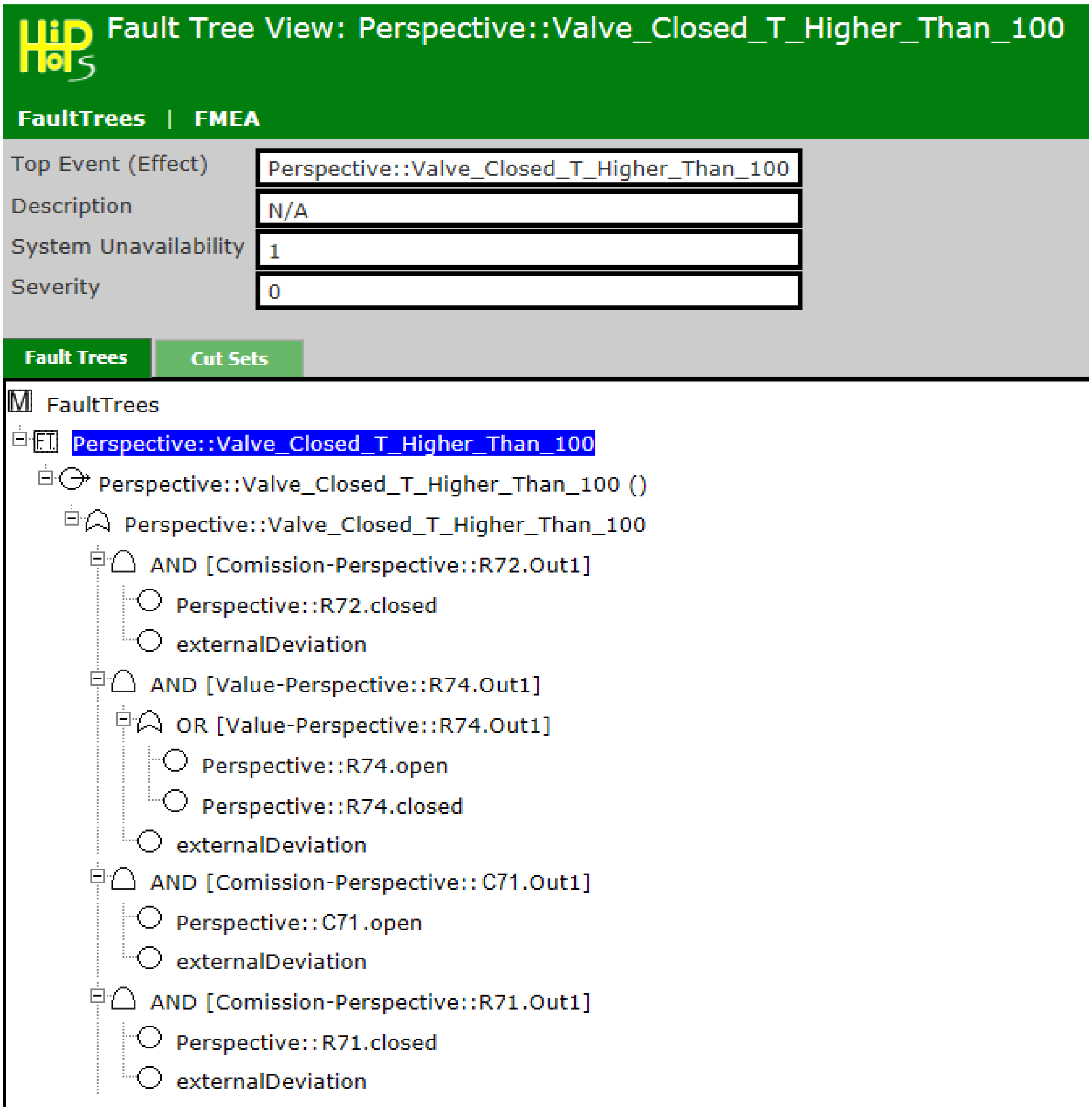
Table 4.18: Minimal cut-Sets of the system failures

Cut-Sets	Order
R3 open	1
R3 drift 2	
R13 open	
R13 closed	
R23 closed	
C13 open	
C71 open AND external	2
R71 closed AND external	
R72 closed AND external	
R74 closed AND external	
R74 open AND external	
Microcontroller all AND (1-dcSM4)	
Microcontroller all AND SM4 Failure	
T71 short AND (1-dcSM1)	
T71 short AND Microcontroller SM1 Failure AND (1-dcSM4)	3
T71 short AND Microcontroller SM1 Failure AND SM4 Failure	

4.4. HiP-HOPS Safety Analysis

The Safety Analysis done to the model described in 4.1.2, using the HiP-HOPS tool, which automatically synthesised the fault tree, is presented in the next few figures.

4.4.1. Fault Trees



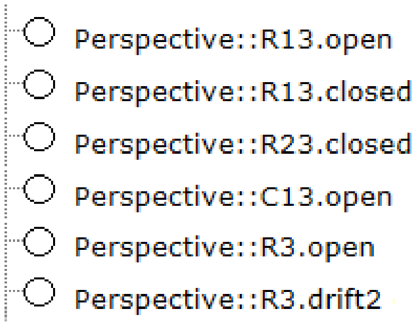
Fault Tree View: Perspective::Valve_Closed_T_Higher_Than_100

Top Event (Effect): Perspective::Valve_Closed_T_Higher_Than_100
Description: N/A
System Unavailability: 1
Severity: 0

```
FaultTrees
  Perspective::Valve_Closed_T_Higher_Than_100
    Perspective::Valve_Closed_T_Higher_Than_100 ()
      Perspective::Valve_Closed_T_Higher_Than_100
        AND [Comission-Perspective::R72.Out1]
          Perspective::R72.closed
          externalDeviation
        AND [Value-Perspective::R74.Out1]
          OR [Value-Perspective::R74.Out1]
            Perspective::R74.open
            Perspective::R74.closed
          externalDeviation
        AND [Comission-Perspective::C71.Out1]
          Perspective::C71.open
          externalDeviation
        AND [Comission-Perspective::R71.Out1]
          Perspective::R71.closed
          externalDeviation
```

Figure 4-11: HiP-HOPS - Fault Tree

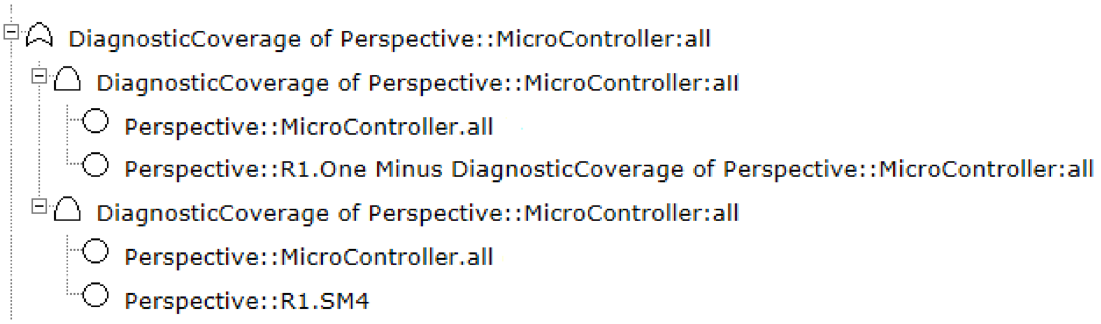
Figure 4-11 shows the general aspect of the internet explorer windows, which contains the results of the safety analysis performed on the model. The top event of the fault tree and the faults that lead to the violation of the safety goal only in combination with external events, are presented.



```
○ Perspective::R13.open
○ Perspective::R13.closed
○ Perspective::R23.closed
○ Perspective::C13.open
○ Perspective::R3.open
○ Perspective::R3.drift2
```

Figure 4-12: HiP-HOPS - Fault Tree

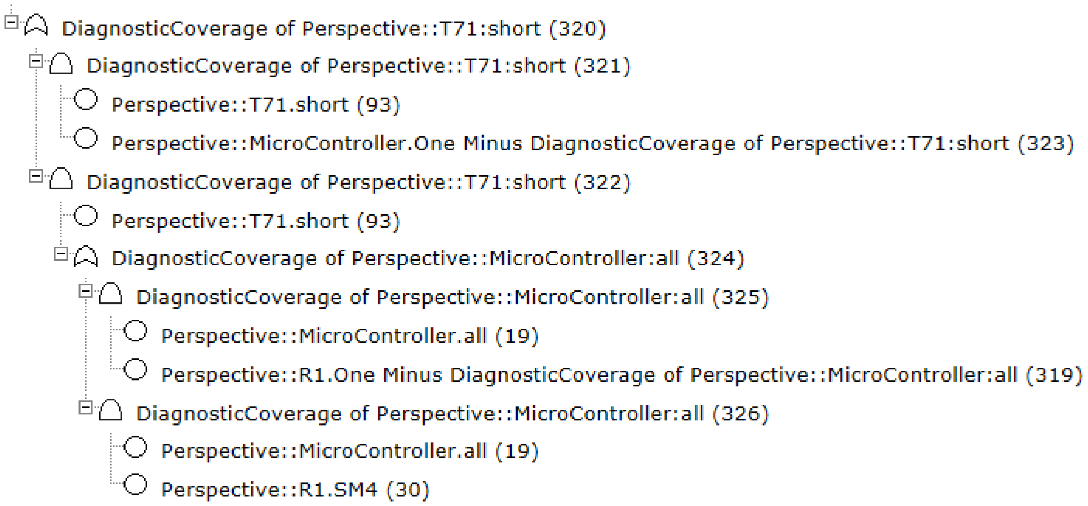
Figure 4-12 represents the section of the fault tree dedicated to the Single-Point Faults.



```
⊟ DiagnosticCoverage of Perspective::MicroController:all
  ⊟ DiagnosticCoverage of Perspective::MicroController:all
      ○ Perspective::MicroController.all
      ○ Perspective::R1.One Minus DiagnosticCoverage of Perspective::MicroController:all
  ⊟ DiagnosticCoverage of Perspective::MicroController:all
      ○ Perspective::MicroController.all
      ○ Perspective::R1.SM4
```

Figure 4-13: HiP-HOPS - Fault Tree

Figure 4-13 is the branch of the fault tree that demonstrates how the microcontroller can lead to the violation of the safety goal. It is slightly different from the one in 4.3. Here, the failure of SM4 is a basic event, which is correct, while in 4.3 that event is the combination of the failure of the WatchDog and an external event. However, for the correct calculation of the probabilistic metric (PMHF, described in 3.5.1), the diagnostic coverage (as a basic event) needs to be connected to the AND port already containing the failure of the microcontroller and the failure of the safety mechanism SM4.



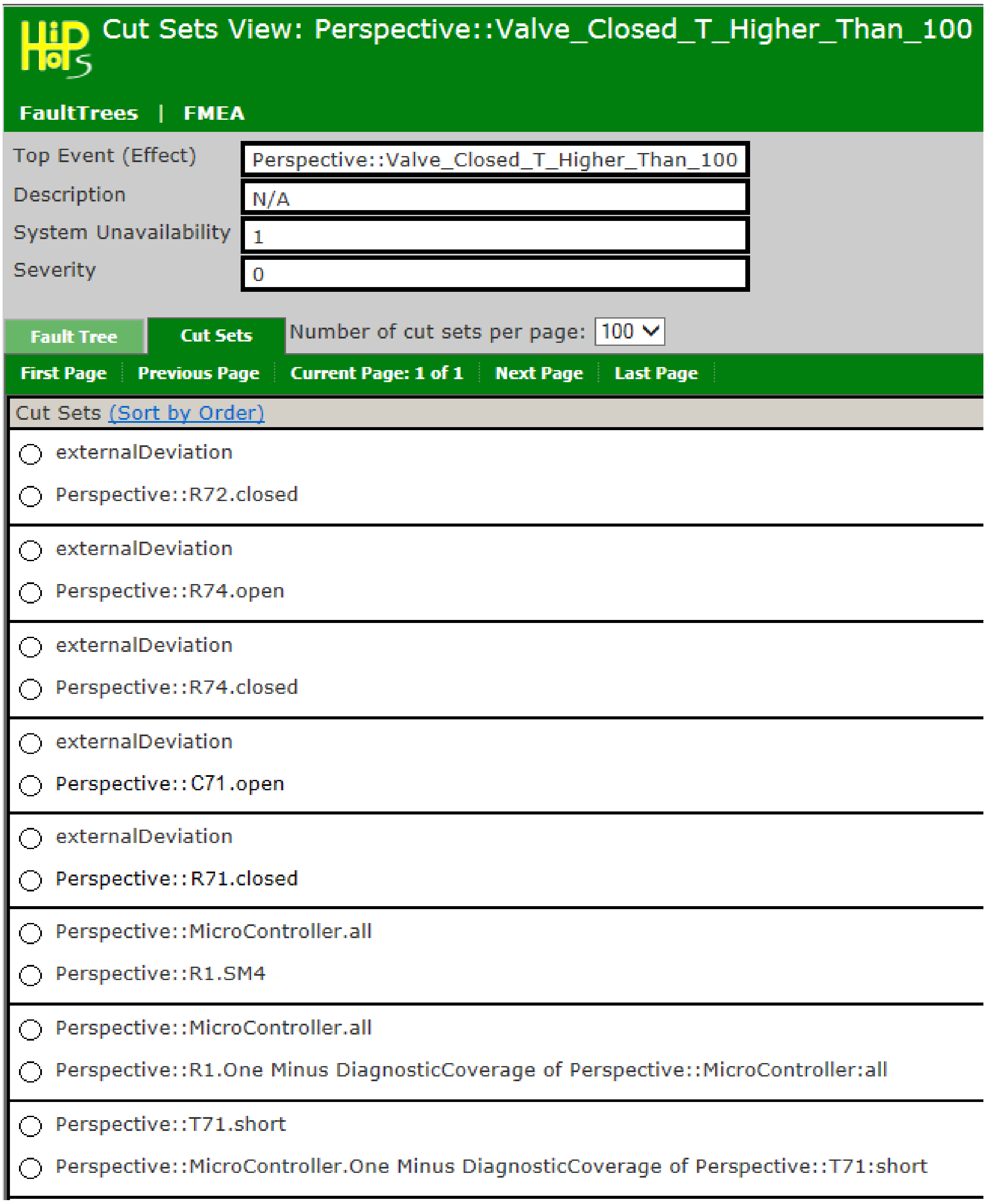
```
⊟ DiagnosticCoverage of Perspective::T71:short (320)
  ⊟ DiagnosticCoverage of Perspective::T71:short (321)
      ○ Perspective::T71.short (93)
      ○ Perspective::MicroController.One Minus DiagnosticCoverage of Perspective::T71:short (323)
  ⊟ DiagnosticCoverage of Perspective::T71:short (322)
      ○ Perspective::T71.short (93)
    ⊟ DiagnosticCoverage of Perspective::MicroController:all (324)
      ⊟ DiagnosticCoverage of Perspective::MicroController:all (325)
          ○ Perspective::MicroController.all (19)
          ○ Perspective::R1.One Minus DiagnosticCoverage of Perspective::MicroController:all (319)
      ⊟ DiagnosticCoverage of Perspective::MicroController:all (326)
          ○ Perspective::MicroController.all (19)
          ○ Perspective::R1.SM4 (30)
```

Figure 4-14: HiP-HOPS - Fault Tree

Figure 4-14 represents the last part of the fault tree and it represents the branch for the failure of the transistor T71. The same can be said for this fault tree, regarding the missing diagnostic coverage.

4.4.2. Cut Sets

The Cut Sets, as said before represent the minimal combination of faults that lead to the hazard. HiP-HOPS generates those Cut Sets automatically. The results can be seen in Figures 4-15 and 4-16.



Cut Sets View: Perspective::Valve_Closed_T_Higher_Than_100

Top Event (Effect)	Perspective::Valve_Closed_T_Higher_Than_100
Description	N/A
System Unavailability	1
Severity	0

Number of cut sets per page: 100

Cut Sets (Sort by Order)

○ externalDeviation
○ Perspective::R72.closed

○ externalDeviation
○ Perspective::R74.open

○ externalDeviation
○ Perspective::R74.closed

○ externalDeviation
○ Perspective::C71.open

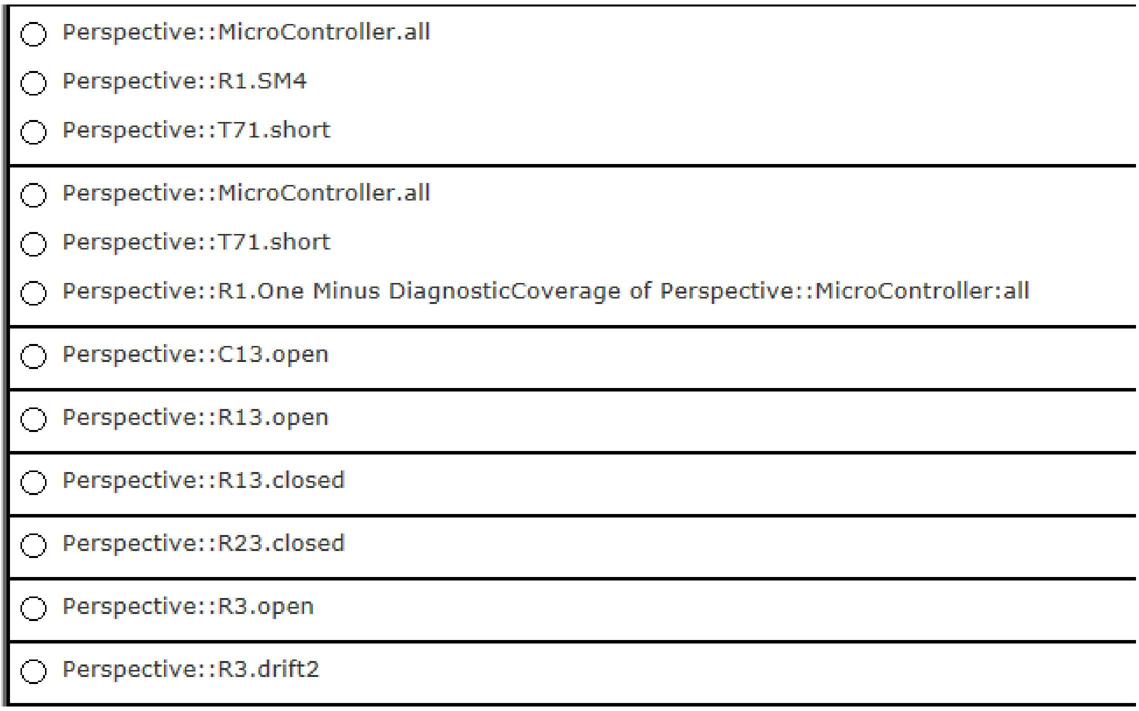
○ externalDeviation
○ Perspective::R71.closed

○ Perspective::MicroController.all
○ Perspective::R1.SM4

○ Perspective::MicroController.all
○ Perspective::R1.One Minus DiagnosticCoverage of Perspective::MicroController:all

○ Perspective::T71.short
○ Perspective::MicroController.One Minus DiagnosticCoverage of Perspective::T71:short

Figure 4-15: HiP-HOPS - Cut Sets



○ Perspective::MicroController.all
○ Perspective::R1.SM4
○ Perspective::T71.short

○ Perspective::MicroController.all
○ Perspective::T71.short
○ Perspective::R1.One Minus DiagnosticCoverage of Perspective::MicroController:all

○ Perspective::C13.open

○ Perspective::R13.open

○ Perspective::R13.closed

○ Perspective::R23.closed

○ Perspective::R3.open

○ Perspective::R3.drift2

Figure 4-16: HiP-HOPS – Cut Sets (continuation)

The two Figures above (4-15 and 4-16) can be compared with the theoretical results stated in Table 4.18 in 4.3.3. Everything is correct, except for the Cut Sets in Figure 4-16, with the following events:

- Microcontroller.all
- T71.short
- R1.SM4/R1.1-DC.Microcontroller

The basic event “all” in the microcontroller has to be replaced by “SM1” which represents the failure of the safety mechanism. It is a minor bug that needs correction.

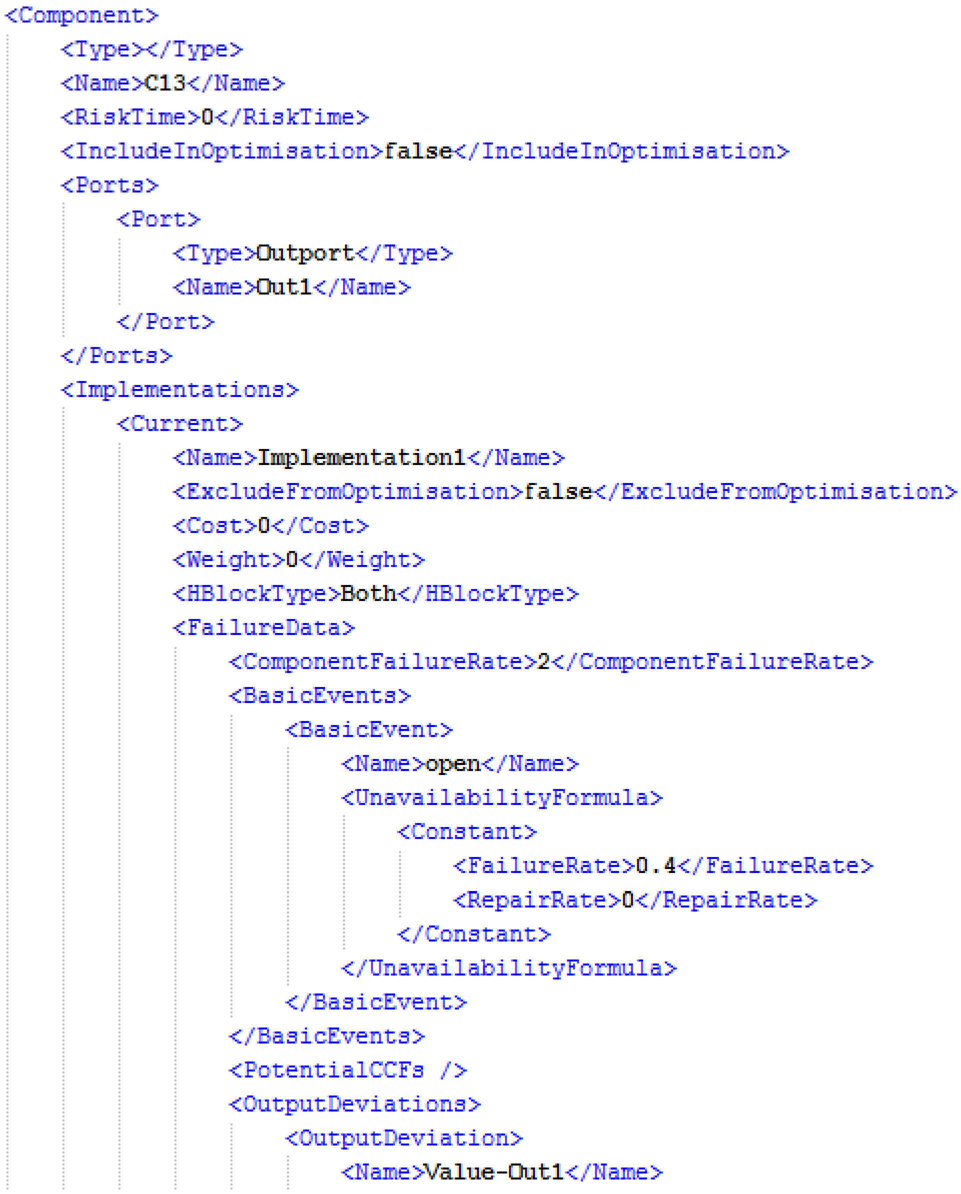
IMPORTANT NOTE: The Component R1 is, in fact, the WatchDog.

4.5. Automatic Calculation of Hardware Metrics

One of the most important objectives of this thesis was to calculate the ISO 26262 hardware architecture evaluation metrics automatically.

When HiP-HOPS analyses one hardware architecture model, first it translates the information in the model to an XML file, like the one in Figure 4-17. Using the information on that XML file, it is possible to calculate the metrics (see 3.4).

A software program was created to accomplish that task of automatically calculating the hardware metrics. A library called tinyXML is used to read and write XML files. With the tinyXML library, the XML tags are treated as nodes, so it is possible to access each node and extract information from it or create new nodes easily.



```
<Component>
    <Type></Type>
    <Name>C13</Name>
    <RiskTime>0</RiskTime>
    <IncludeInOptimisation>false</IncludeInOptimisation>
    <Ports>
        <Port>
            <Type>Outport</Type>
            <Name>Out1</Name>
        </Port>
    </Ports>
    <Implementations>
        <Current>
            <Name>Implementation1</Name>
            <ExcludeFromOptimisation>false</ExcludeFromOptimisation>
            <Cost>0</Cost>
            <Weight>0</Weight>
            <HBlockType>Both</HBlockType>
            <FailureData>
                <ComponentFailureRate>2</ComponentFailureRate>
                <BasicEvents>
                    <BasicEvent>
                        <Name>open</Name>
                        <UnavailabilityFormula>
                            <Constant>
                                <FailureRate>0.4</FailureRate>
                                <RepairRate>0</RepairRate>
                            </Constant>
                        </UnavailabilityFormula>
                    </BasicEvent>
                </BasicEvents>
                <PotentialCCFs />
                <OutputDeviations>
                    <OutputDeviation>
                        <Name>Value-Out1</Name>
```

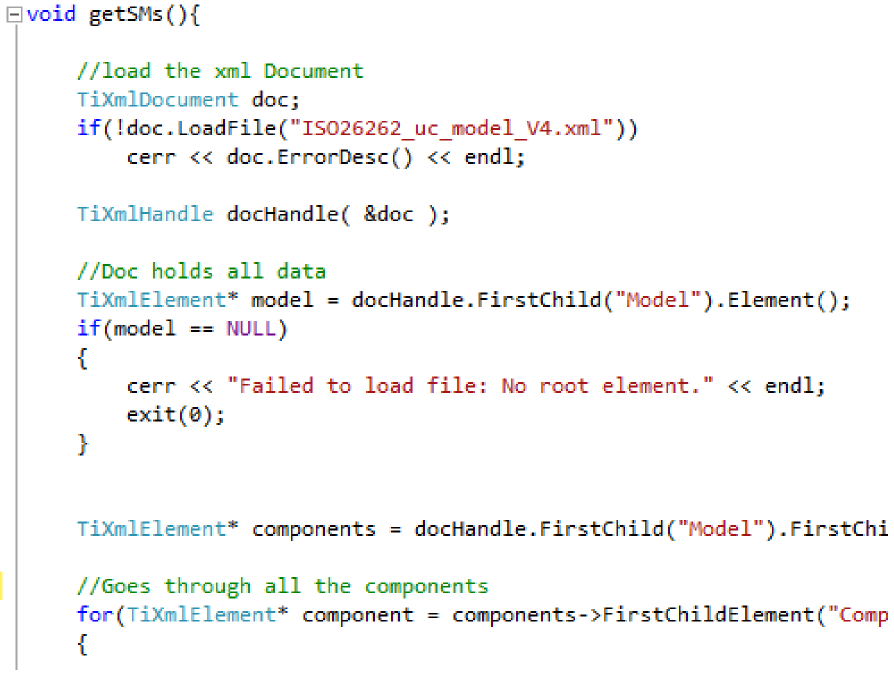
Figure 4-17: Example of a component (C13) in the XML file

4.5.1. Hardware Metrics Software

In this section, the algorithm of the program is briefly explained and some parts of the code are shown to better illustrate it. The software goes through the following steps:

1. Check which components are safety mechanisms, by going through all of them. That information, comprised by the name of the component (e.g.: microcontroller) and

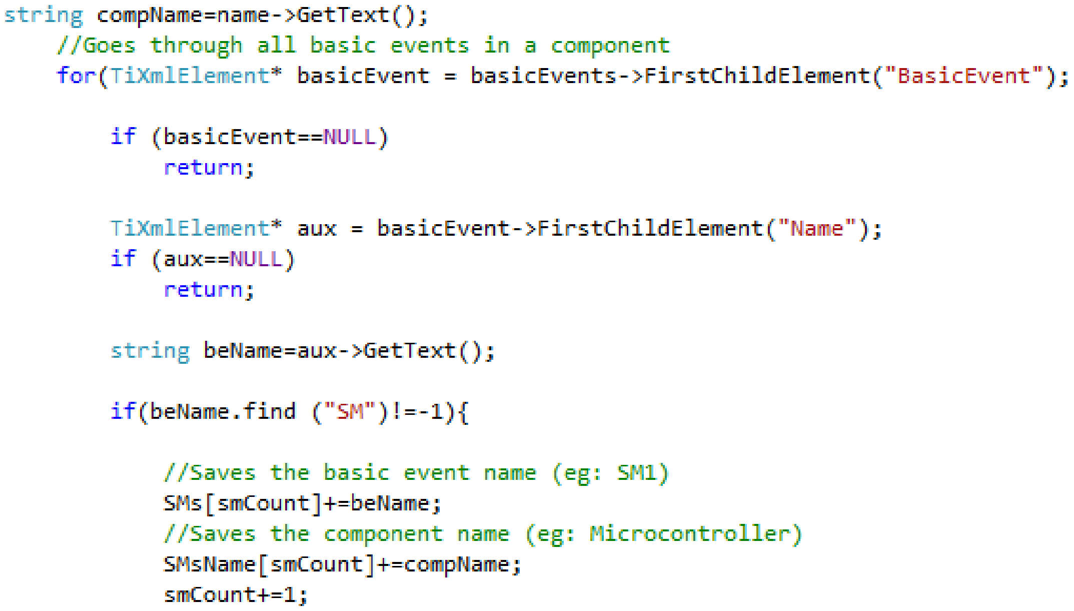
name of the safety mechanism (e.g.: SM1), is saved in two global string arrays. Figures 4-18 and 4-19 are extracts of the function that performs that task.



```
void getSMs(){

    //load the xml Document
    TiXmlDocument doc;
    if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
        cerr << doc.ErrorDesc() << endl;

    TiXmlHandle docHandle( &doc );

    //Doc holds all data
    TiXmlElement* model = docHandle.FirstChild("Model").Element();
    if(model == NULL)
    {
        cerr << "Failed to load file: No root element." << endl;
        exit(0);
    }


    TiXmlElement* components = docHandle.FirstChild("Model").FirstChi

    //Goes through all the components
    for(TiXmlElement* component = components->FirstChildElement("Comp
    {
```

Figure 4-18: Extract of the function to know the safety mechanisms - part 1

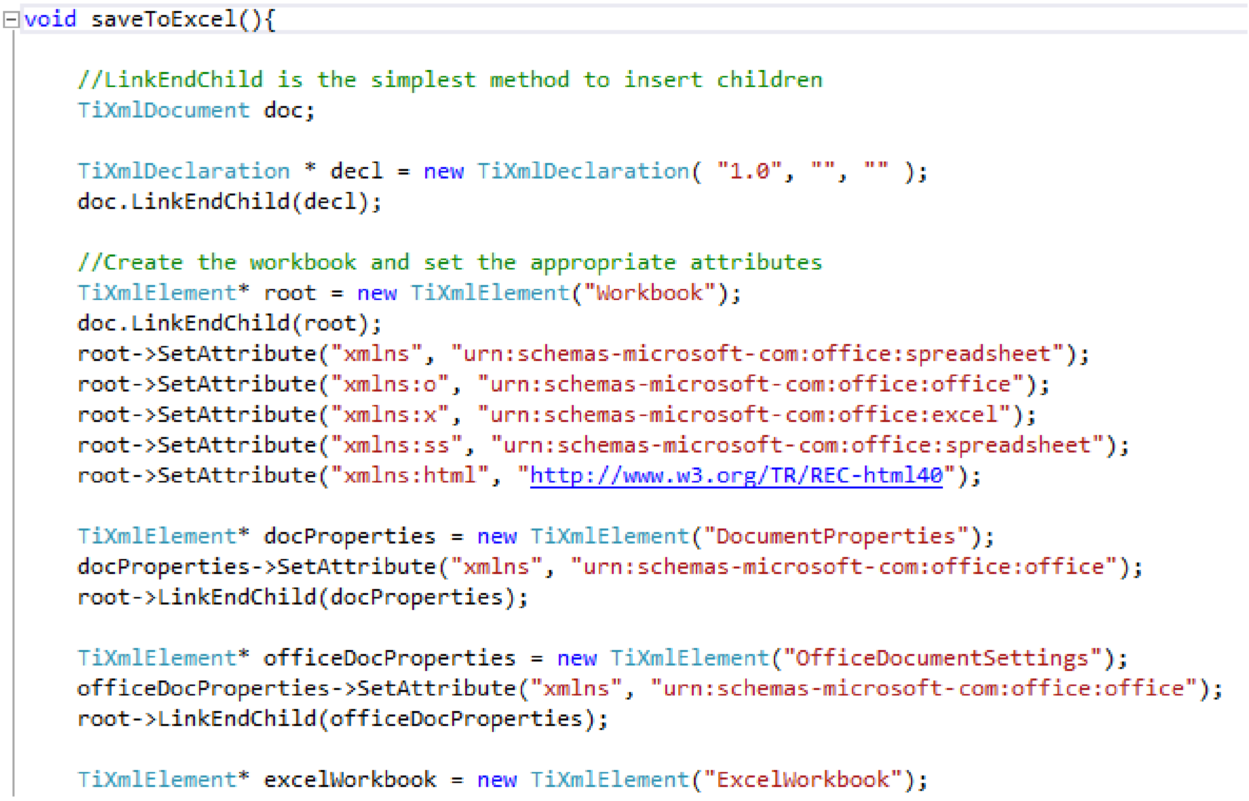
(…)



```
string compName=name->GetText();
    //Goes through all basic events in a component
    for(TiXmlElement* basicEvent = basicEvents->FirstChildElement("BasicEvent");

        if (basicEvent==NULL)
            return;

        TiXmlElement* aux = basicEvent->FirstChildElement("Name");
        if (aux==NULL)
            return;

        string beName=aux->GetText();

        if(beName.find ("SM")!=-1){

            //Saves the basic event name (eg: SM1)
            SMs[smCount]+=beName;
            //Saves the component name (eg: Microcontroller)
            SMsName[smCount]+=compName;
            smCount+=1;
```

Figure 4-19: Extract of the function to know the safety mechanisms - part 2

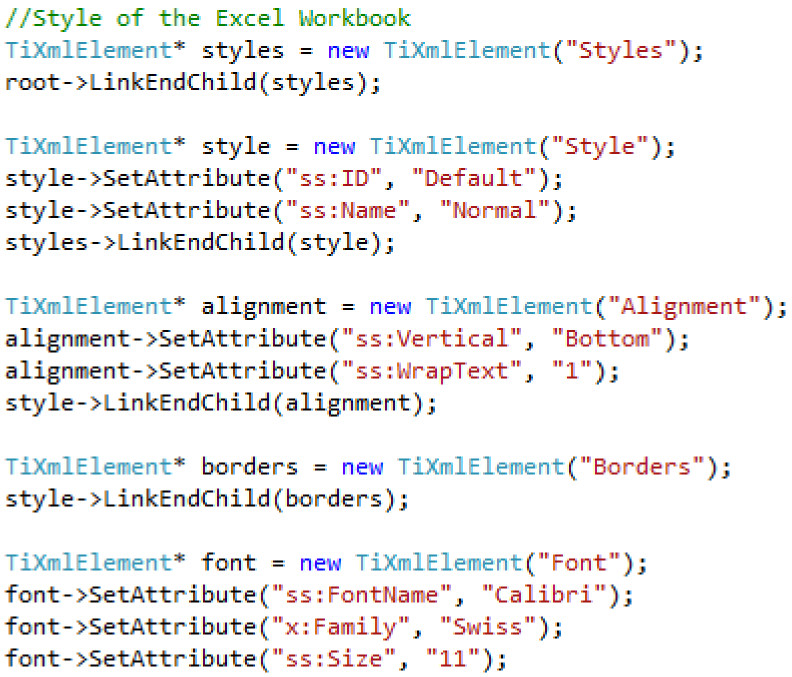
2. Create the setup for the excel XML file. An example of that code, setting up the excel workbook is present in Figure 4-20.



```
void saveToExcel(){

    //LinkEndChild is the simplest method to insert children
    TiXmlDocument doc;

    TiXmlDeclaration * decl = new TiXmlDeclaration( "1.0", "", "" );
    doc.LinkEndChild(decl);

    //Create the workbook and set the appropriate attributes
    TiXmlElement* root = new TiXmlElement("Workbook");
    doc.LinkEndChild(root);
    root->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:spreadsheet");
    root->SetAttribute("xmlns:o", "urn:schemas-microsoft-com:office:office");
    root->SetAttribute("xmlns:x", "urn:schemas-microsoft-com:office:excel");
    root->SetAttribute("xmlns:ss", "urn:schemas-microsoft-com:office:spreadsheet");
    root->SetAttribute("xmlns:html", "http://www.w3.org/TR/REC-html40");

    TiXmlElement* docProperties = new TiXmlElement("DocumentProperties");
    docProperties->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:office");
    root->LinkEndChild(docProperties);

    TiXmlElement* officeDocProperties = new TiXmlElement("OfficeDocumentSettings");
    officeDocProperties->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:office");
    root->LinkEndChild(officeDocProperties);

    TiXmlElement* excelWorkbook = new TiXmlElement("ExcelWorkbook");
```

Figure 4-20: Extract of the setup for the document

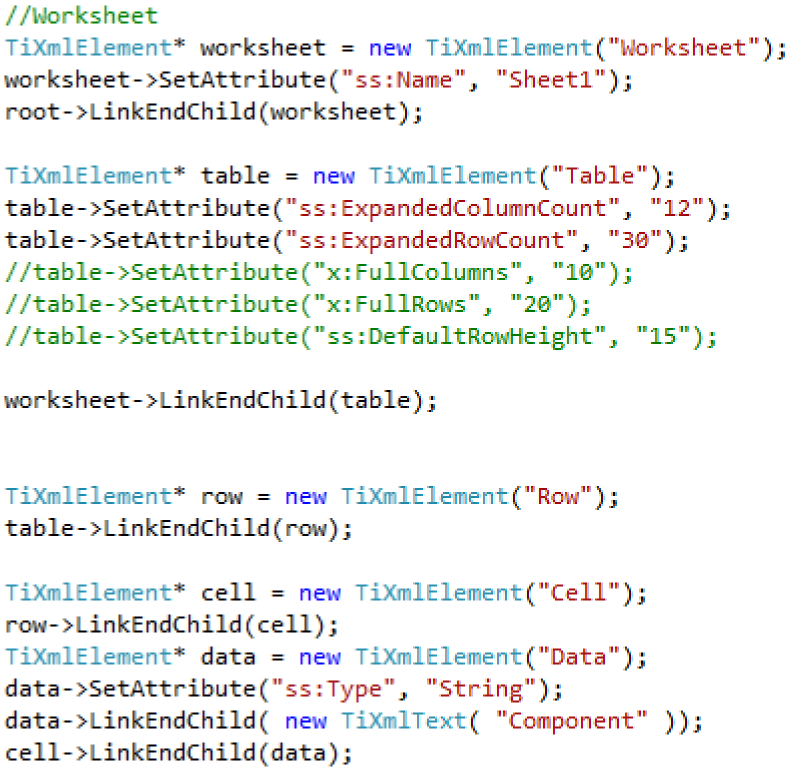
3. Setup the style of the workbook. Figure 4-21 presents an example of that code.



```
//Style of the Excel Workbook
TiXmlElement* styles = new TiXmlElement("Styles");
root->LinkEndChild(styles);

TiXmlElement* style = new TiXmlElement("Style");
style->SetAttribute("ss:ID", "Default");
style->SetAttribute("ss:Name", "Normal");
styles->LinkEndChild(style);

TiXmlElement* alignment = new TiXmlElement("Alignment");
alignment->SetAttribute("ss:Vertical", "Bottom");
alignment->SetAttribute("ss:WrapText", "1");
style->LinkEndChild(alignment);

TiXmlElement* borders = new TiXmlElement("Borders");
style->LinkEndChild(borders);

TiXmlElement* font = new TiXmlElement("Font");
font->SetAttribute("ss:FontName", "Calibri");
font->SetAttribute("x:Family", "Swiss");
font->SetAttribute("ss:Size", "11");
```

Figure 4-21: Extract of the workbook style setup

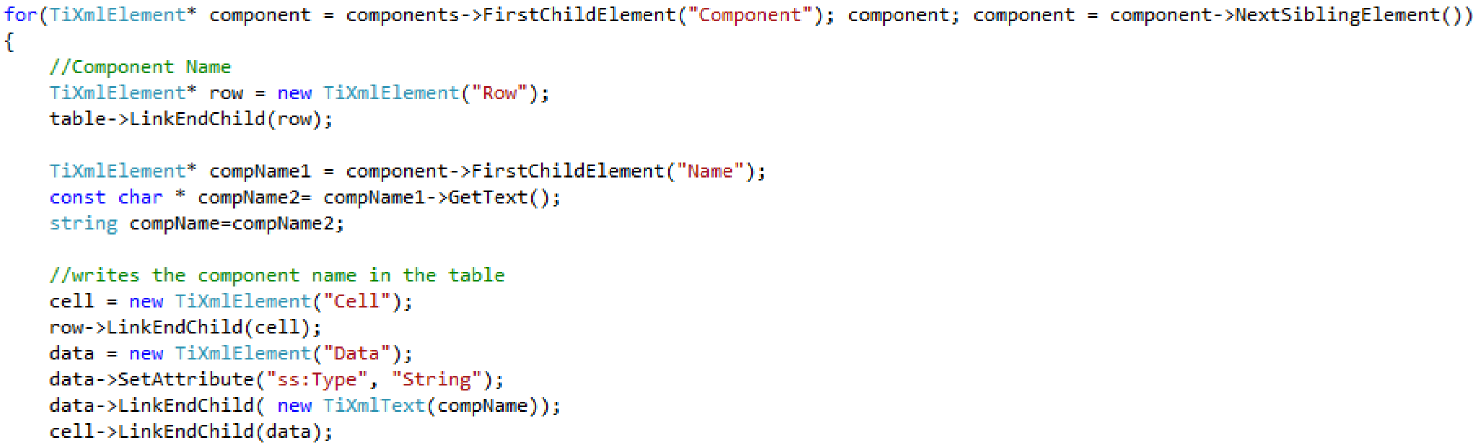
4. Create the table, with the respective column names. Figure 4-22 presents that example.



```
//Worksheet
TiXmlElement* worksheet = new TiXmlElement("Worksheet");
worksheet->SetAttribute("ss:Name", "Sheet1");
root->LinkEndChild(worksheet);

TiXmlElement* table = new TiXmlElement("Table");
table->SetAttribute("ss:ExpandedColumnCount", "12");
table->SetAttribute("ss:ExpandedRowCount", "30");
//table->SetAttribute("x:FullColumns", "10");
//table->SetAttribute("x:FullRows", "20");
//table->SetAttribute("ss:DefaultRowHeight", "15");

worksheet->LinkEndChild(table);


TiXmlElement* row = new TiXmlElement("Row");
table->LinkEndChild(row);

TiXmlElement* cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
TiXmlElement* data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Component" ));
cell->LinkEndChild(data);
```

Figure 4-22: Creation of the table and the column for the components names

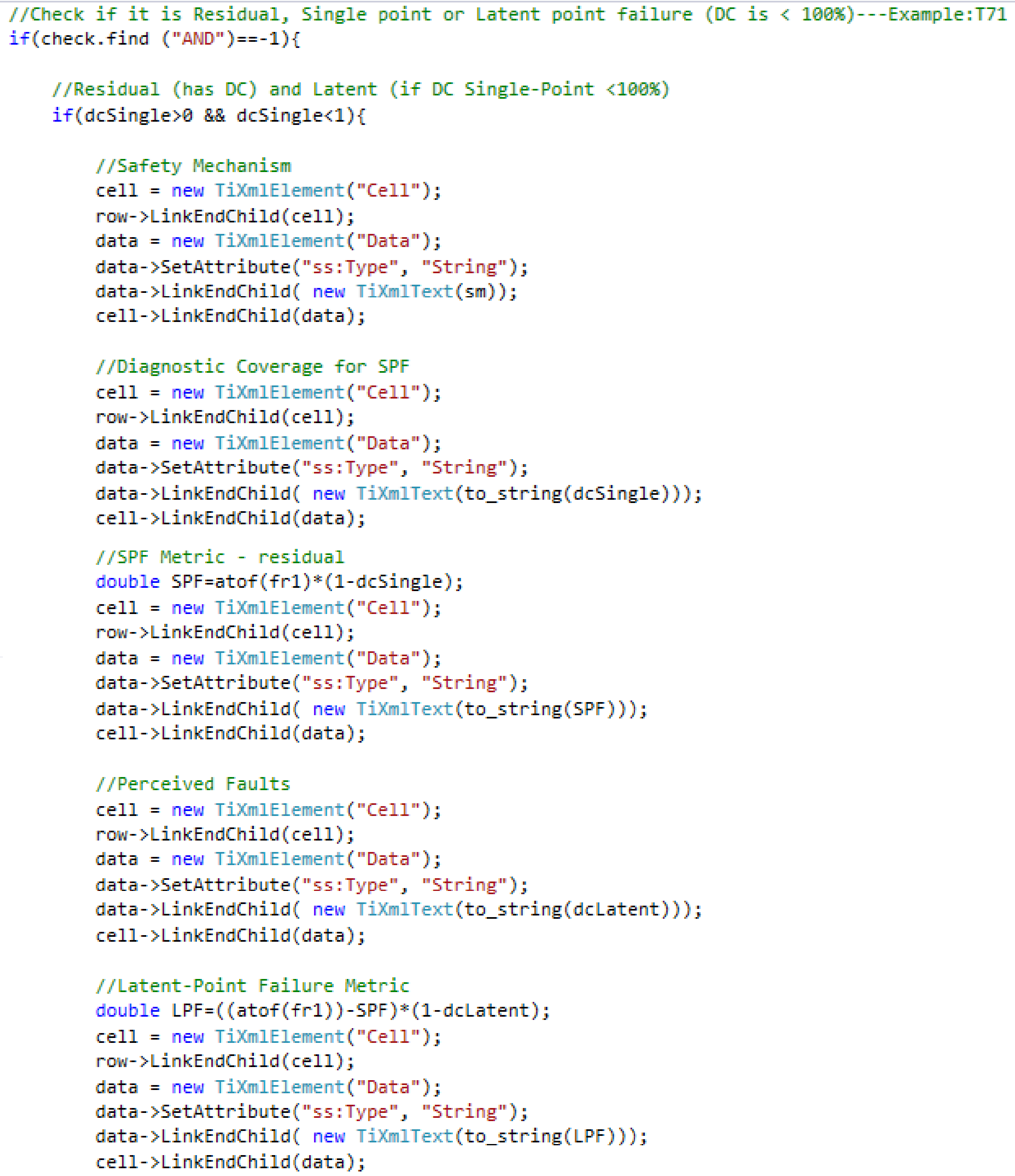
5. Start going through the components and writing information on the table. Figure 4-23 presents an example of that.



```
for(TiXmlElement* component = components->FirstChildElement("Component"); component; component = component->NextSiblingElement())
{
    //Component Name
    TiXmlElement* row = new TiXmlElement("Row");
    table->LinkEndChild(row);

    TiXmlElement* compName1 = component->FirstChildElement("Name");
    const char * compName2= compName1->GetText();
    string compName=compName2;

    //writes the component name in the table
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);
    data = new TiXmlElement("Data");
    data->SetAttribute("ss:Type", "String");
    data->LinkEndChild( new TiXmlText(compName));
    cell->LinkEndChild(data);
```

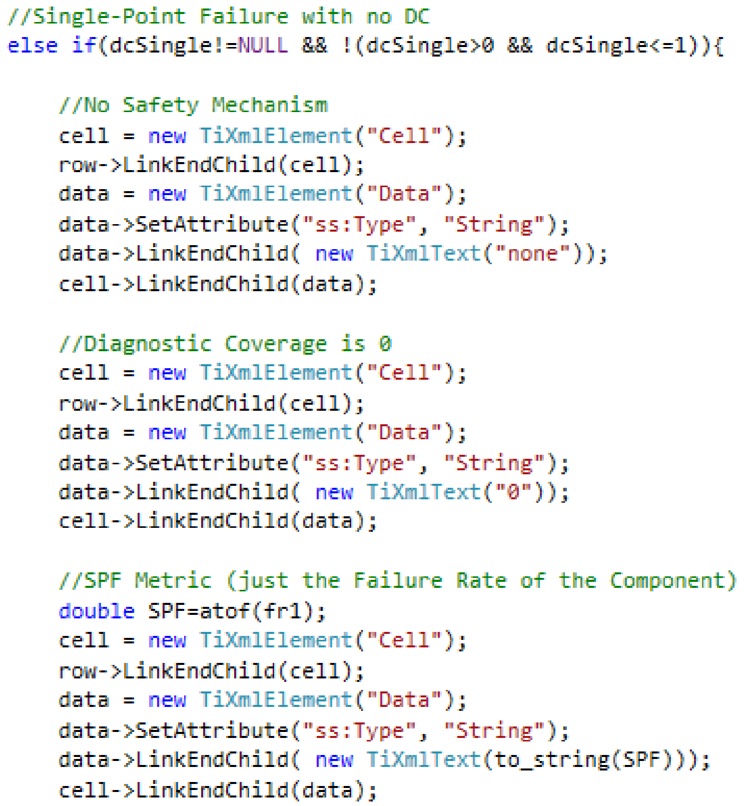
Figure 4-23: Components loop and writing of the component name

6. Calculate the residual/single-point or latent fault failure rate, using the equations in 3.4. Figure 4-24 represents that for residual faults, figure 4-25 for single-point faults and figure 4-26 for multiple-point faults.



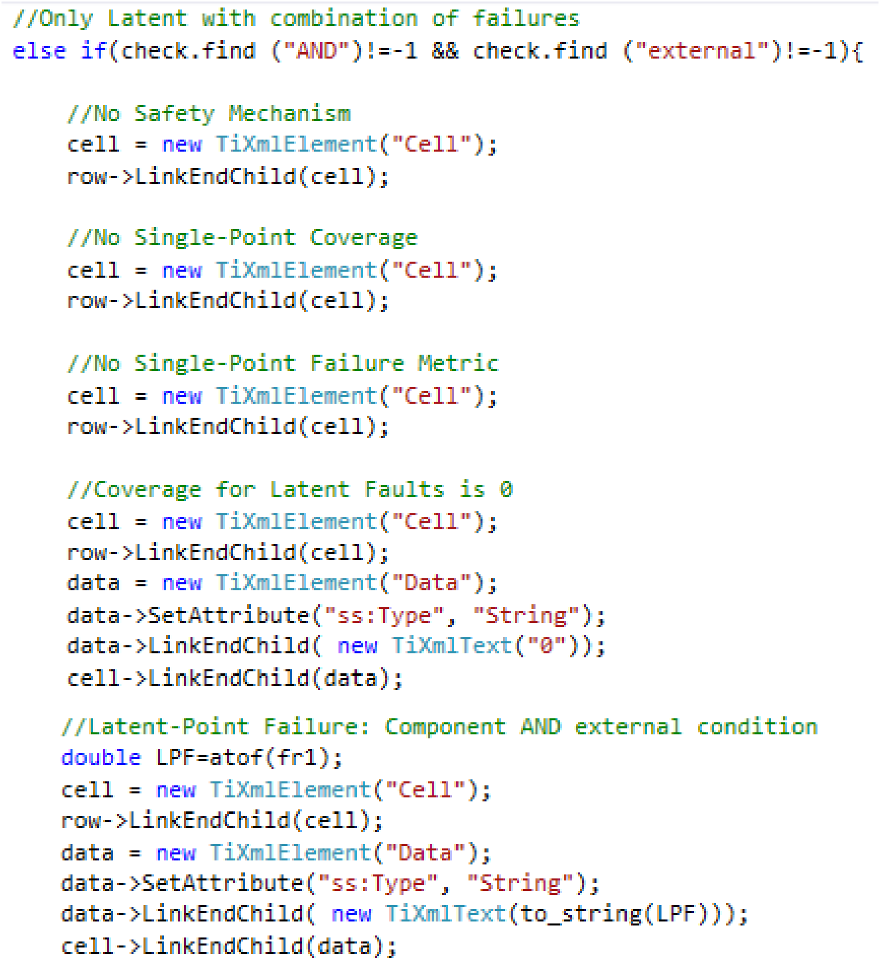
```
//Check if it is Residual, Single point or Latent point failure (DC is < 100%)---Example:T71
if(check.find ("AND")==-1){

    //Residual (has DC) and Latent (if DC Single-Point <100%)
    if(dcSingle>0 && dcSingle<1){

        //Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(sm));
        cell->LinkEndChild(data);

        //Diagnostic Coverage for SPF
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcSingle)));
        cell->LinkEndChild(data);

        //SPF Metric - residual
        double SPF=atof(fr1)*(1-dcSingle);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(SPF)));
        cell->LinkEndChild(data);

        //Perceived Faults
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcLatent)));
        cell->LinkEndChild(data);

        //Latent-Point Failure Metric
        double LPF=((atof(fr1))-SPF)*(1-dcLatent);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(LPF)));
        cell->LinkEndChild(data);
```

Figure 4-24: Calculations for Residual Faults



```
//Single-Point Failure with no DC
else if(dcSingle!=NULL && !(dcSingle>0 && dcSingle<=1)){

    //No Safety Mechanism
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);
    data = new TiXmlElement("Data");
    data->SetAttribute("ss:Type", "String");
    data->LinkEndChild( new TiXmlText("none"));
    cell->LinkEndChild(data);

    //Diagnostic Coverage is 0
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);
    data = new TiXmlElement("Data");
    data->SetAttribute("ss:Type", "String");
    data->LinkEndChild( new TiXmlText("0"));
    cell->LinkEndChild(data);

    //SPF Metric (just the Failure Rate of the Component)
    double SPF=atof(fr1);
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);
    data = new TiXmlElement("Data");
    data->SetAttribute("ss:Type", "String");
    data->LinkEndChild( new TiXmlText(to_string(SPF)));
    cell->LinkEndChild(data);
```

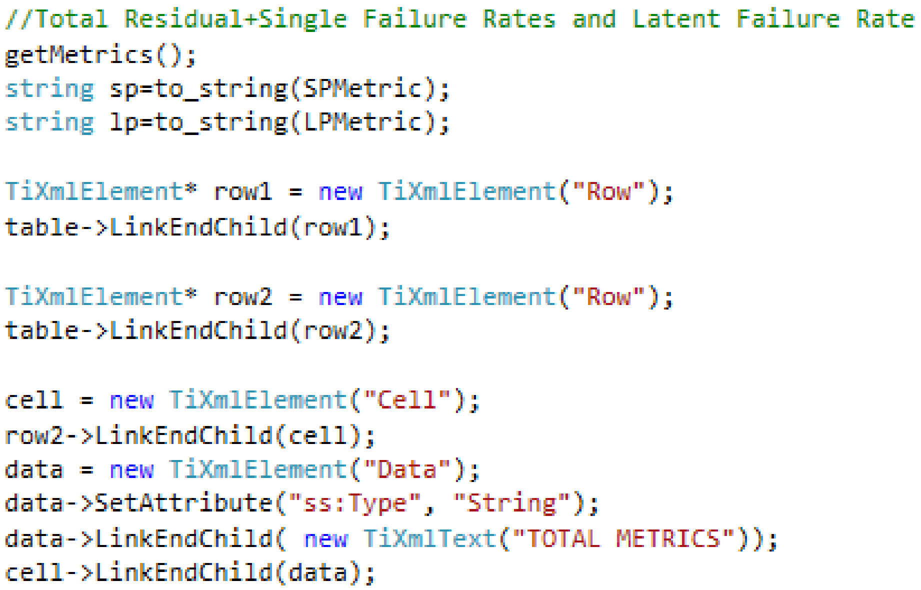
Figure 4-25: Calculations for Single-Point Faults



```
//Only Latent with combination of failures
else if(check.find ("AND")!=-1 && check.find ("external")!=-1){

    //No Safety Mechanism
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);

    //No Single-Point Coverage
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);

    //No Single-Point Failure Metric
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);

    //Coverage for Latent Faults is 0
    cell = new TiXmlElement("Cell");
    row->LinkEndChild(cell);
    data = new TiXmlElement("Data");
    data->SetAttribute("ss:Type", "String");
    data->LinkEndChild( new TiXmlText("0"));
    cell->LinkEndChild(data);

   //Latent-Point Failure: Component AND external condition
   double LPF=atof(fr1);
   cell = new TiXmlElement("Cell");
   row->LinkEndChild(cell);
   data = new TiXmlElement("Data");
   data->SetAttribute("ss:Type", "String");
   data->LinkEndChild( new TiXmlText(to_string(LPF)));
   cell->LinkEndChild(data);
```

Figure 4-26: Calculations for Multiple-Point Faults (no safety mechanism)

7. Finally, calculate the metrics, through the function “getMetrics” and write them in the excel table. Figure 4-27 represents an extract of that process.



```
//Total Residual+Single Failure Rates and Latent Failure Rate
getMetrics();
string sp=to_string(SPMetric);
string lp=to_string(LPMetric);

TiXmlElement* row1 = new TiXmlElement("Row");
table->LinkEndChild(row1);

TiXmlElement* row2 = new TiXmlElement("Row");
table->LinkEndChild(row2);

cell = new TiXmlElement("Cell");
row2->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText("TOTAL METRICS"));
cell->LinkEndChild(data);
```

Figure 4-27: Calculation of the Metrics

4.5.2. Hardware Metrics Results

The final aspect of the results table is presented in the Table in appendix B. As expected, the results are the same as the ones in ISO 26262 – part 5 Annex E, except for the metrics results, due to the total failure rate, sum of the failure rates of all the safety-related components. There is a bug in the function that calculates the total failure rate, as it considers also the non-safety related components. As future work, the simple bug must be fixed.

The Safety Goal is assigned with ASIL B. Table 3.4 in 3.4.1.3 specifies a single-point fault metric recommendation of ≥ 90 % and Table 3.5 specifies a latent fault metric recommendation of ≥ 60 %.

The Single-Point Fault Metric result is 93.39 % (it should be 93.2 %), so it satisfies the target value set by ISO 26262. The same for the Latent-Point Fault Metric that with 90.28 % (it should be 90 %) also satisfies its target value.

If the results weren’t in tune with the targets, then more safety mechanisms should be implemented, or the implemented ones should be changed to more efficient techniques. The other alternative would be to use components with lower failure rates (usually more expensive, depending on its complexity).

4.6. Summary

In this chapter, the chosen hardware architecture to validate the metrics results was presented, and its operation explained. The failure propagation model of the chosen system was outlined along with the failure annotations of the system's components. Having the model, it was possible to perform safety analysis. The fault tree for this system was manually created in order to compare the results (fault tree and cut-sets) with the HiP-HOPS analysis. The latter was changed to include safety mechanisms. Finally, the algorithm of the program created to automatically calculate the hardware evaluation metrics is explained.

Chapter 5

Conclusion

The vehicles developed in the near future, will have most of their critical functions, such as steering and braking, controlled by systems containing electrical, electronic and programmable electronic components. Not to mention cars that integrate hybrid technologies. These changes are being implemented to increase the vehicle's commodities and safety and decrease fuel consumption through a more adequate driving behavior. To assure that those systems are the most reliable they can be, Functional Safety Standards, such as IEC 61508 or ISO 26262 (specially created for road vehicles) aid the developers with guidelines for their development. One important measure to guarantee the reliability of these systems is to add safety mechanisms. These detect failures in the systems and activate measures that control them and avoid safety goal violation.

As this type of systems, suffer changes throughout the development process, it is important to test those changes during that process and not only in the beginning or when system failures occur. With that in mind, Safety Analysis tools, like HiP-HOPS were created.

In this thesis, safety mechanisms were included in the HiP-HOPS analysis, by changing the code. Also, a C++ software program (Appendix C) was developed to automatically calculate the hardware evaluation metrics, proposed in ISO 26262. These metrics allow the system designer to compare different system architectures.

The relevance of the work developed is be discussed in the next sections and the final considerations about it are presented. To finalize, possible future changes to HiP-HOPS, regarding hardware evaluation and developments to the software program are presented.

5.1. Final Considerations

The results achieved in the Safety Analysis done through HiP-HOPS namely the Fault Trees and Cut Sets, comply with the ideas stated in ISO 26262 in regard to safety mechanism modelling. Furthermore, the Fault Trees produced by HiP-HOPS are now capable of dealing with the probabilistic metric (PMHF).

The software program for the automatic calculation of the Hardware Evaluation Metrics (Single-Point Metric and Latent-Point Metric), is capable of producing a results table that allows the system designer to check if the metrics target values have been achieved. If they haven't, the designer needs to change components or implement more efficient safety mechanisms. The table provides all the failure information regarding the components and its safety mechanisms. If the user combines the HiP-HOPS resulting Cut Sets with the Metrics Table, then it is possible to quickly understand which components need to be changed. This software program has a small bug in the calculations, as it considers not-safe related components in the total failure rate calculation.

The model tested is quite simple, but it was important to test the metric results of the software program against the ones in ISO 26262.

This work was relevant for the following reasons:

1. It changed HiP-HOPS so its Safety Analysis can comply with the safety mechanisms described in ISO 26262 – part 5;

IMPORTANT NOTE: HiP-HOPS is a commercial product, therefore, the changes made to its code will not appear in this document.

2. It provides system designers with means to evaluate hardware architectures, while complying with the standard ISO 26262;

5.2. Further Developments

As said in section 5.1, some bugs in the Metrics Software Program need to be attended, although it is not really critical. This program is currently a separate entity, it should be interesting to include it directly in the HiP-HOPS tools, to make it more user friendly.

HiP-HOPS now complies with Safety Mechanisms, therefore it is possible to perform probability evaluation for hardware systems, using the PMHF technique described in 3.5.1. After the Safety Analysis, the technique could be used to provide a complementary method of evaluating the hardware architecture. It is also necessary to correct the minor bugs mentioned in 4.3.3.

It should be interesting to test the thesis resulting products, Metrics Software and safety Mechanism addition, using a different, more complex, hardware architecture. The Hybrid Braking System, created to test the HiP-HOPS automatic ASIL allocation is an interesting possibility.

References

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[3] Adachi, M., Papadopoulos, Y., Sharvia, S., Parker and D., Tohdo, T. (2011). "An approach to optimization of fault tolerant architectures using HiP-HOPS." Software - Practice and Experience 41(11): 1303-1327.

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[12] Sinha, P. (2011). "Architectural design and reliability analysis of a fail-operational brake-by-wire system from ISO 26262 perspectives." Reliability Engineering and System Safety.

[13] Hillenbrand, M., Heinz, M., Adler, N., Matheis, J. and Müller-Glaser, K. D. (2010). "Failure mode and effect analysis based on electric and electronic architectures of vehicles to support the safety lifecycle ISO/DIS 26262."

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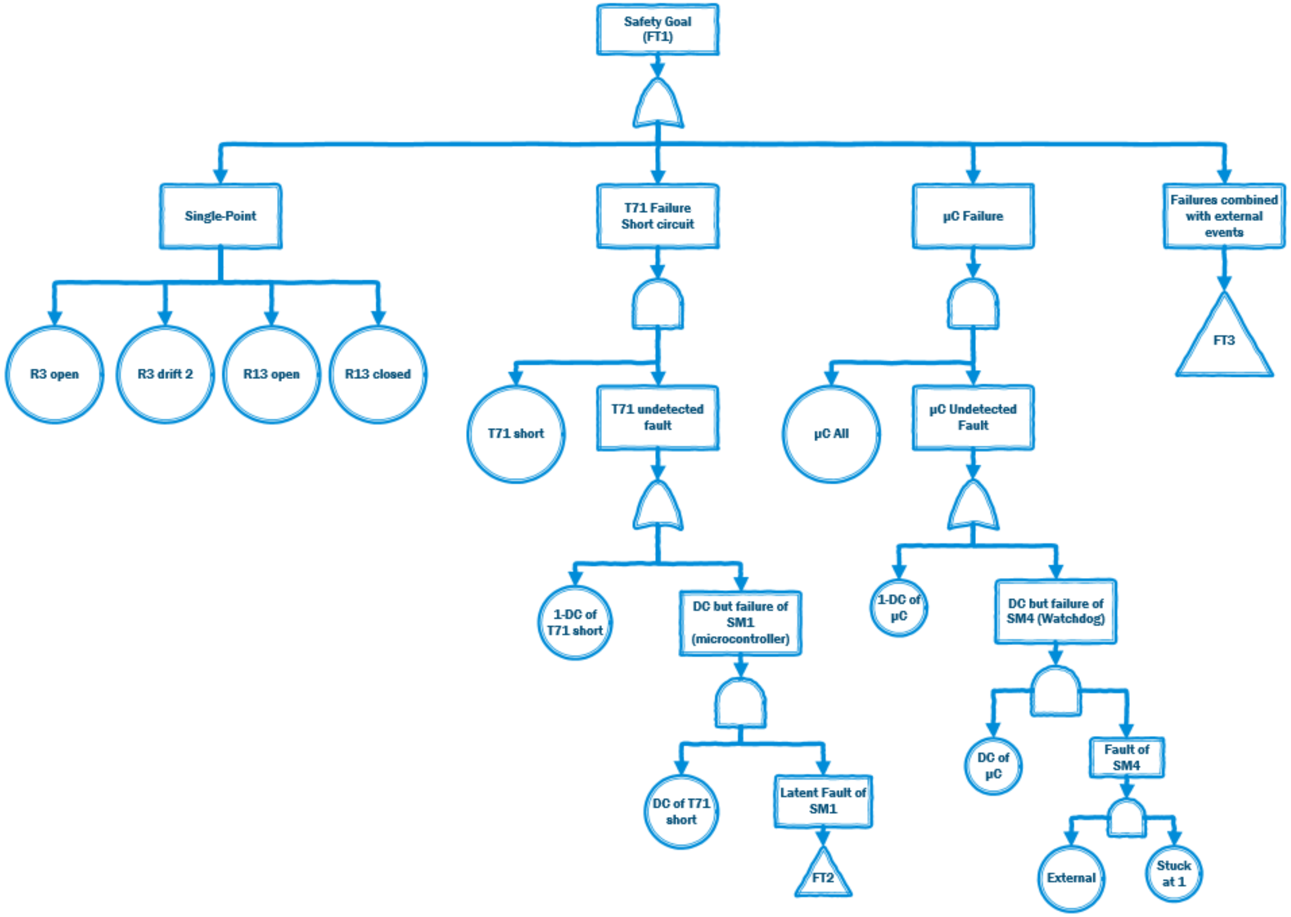
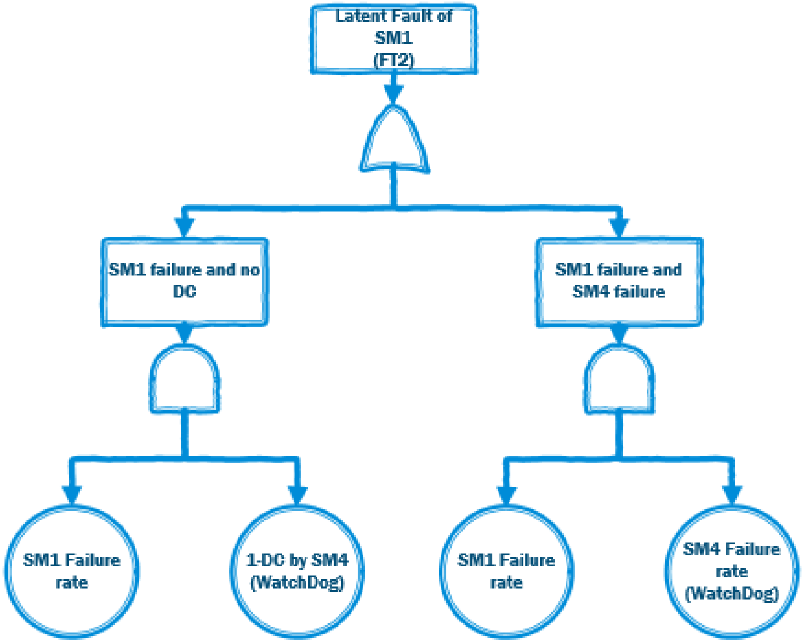
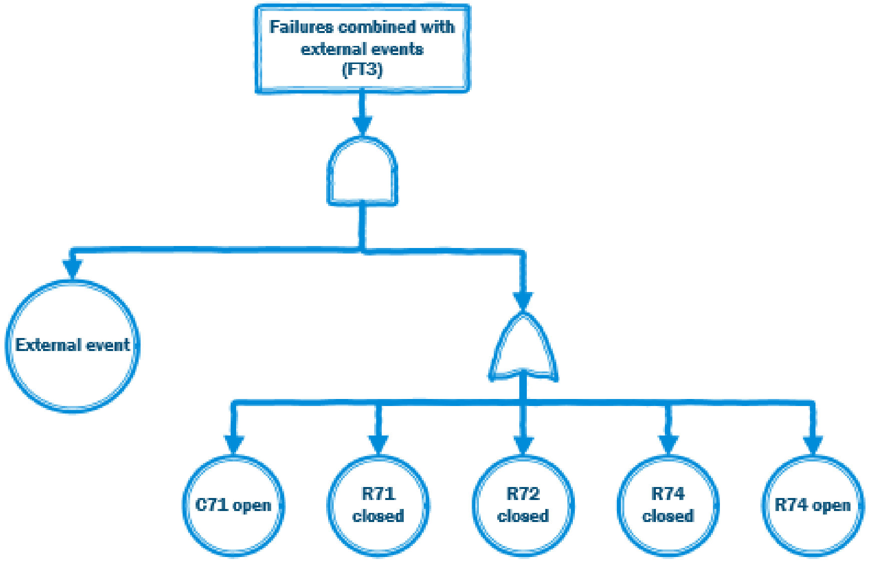
Appendix A - Manually created Fault Trees

A.1. Main Fault Tree



A.2. Secondary Fault Trees


Latent Fault of SM1 (FT2)
SM1 failure and no DC
SM1 failure and SM4 failure
SM1 Failure rate
1-DC by SM4 (WatchDog)
SM1 Failure rate
SM4 Failure rate (WatchDog)



Appendix B

Metrics Calculation Software Results

Component	Failure Rate	Failure Mode	Failure Mode Failure Rate	Safety Mechanism preventing safety goal violation?	Failure Mode Coverage	Residual/Single-point fault Failure Rate	Failure Mode Coverage in respect to Latent Faults	Latent-Point Fault Failure Rate
C13	2	open	0.4	none	0	0.400000		
C23	2							
C71	2	open	0.4				0	0.400000
I71	5							
MicroController	100	all	50	none	0.900000	5.000000	1.000000	0.000000
WatchDog	20	OutStuck1	10				0	10.000000
R13	2	open	1.8	none	0	1.800000		
		closed	0.2	none	0	0.200000		
R23	2	closed	0.2	none	0	0.200000		
R3	3	open	0.9	none	0	0.900000		

		drift2	0.9	none	0	0.900000		
R71	2	closed	0.2				0	0.200000
R72	2	closed	0.2				0	0.200000
R73	2							
R74	2	open	1.8				0	1.800000
		closed	0.2				0	0.200000
T71	5	short	2.5	SM1	0.900000	0.250000	0.800000	0.450000

TOTAL METRICS					9.650000		13.250000	

Single-Point Metric	0.933904
Latent-Point Metric	0.902824

Appendix C

Metrics Software

This appendix contains the whole code of the Metrics Calculation Software.

```
#include <stdio.h>
#include <iostream>
#include "tinyxml.h"
#include "string.h"
#include <vector>
#include <fstream>

using namespace std;

double totalFailureRate;
bool isSPF;
bool isLPF;
double SPMetric;
double LPMetric;
string SMs[20];
int smCount;
string SMsName[20];

void GetTotalFailureRate(){

	//load the xml Document
	TiXmlDocument doc;
	if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
		cerr << doc.ErrorDesc() << endl;
```

```
    TiXmlHandle docHandle( &doc );

    //Doc holds all data
    TiXmlElement* model = docHandle.FirstChild("Model").Element();
    if(model == NULL)
    {
        cerr << "Failed to load file: No root element." << endl;
        exit(0);
    }


    TiXmlElement* components =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();

    for(TiXmlElement* component = components->FirstChildElement("Component"); component != NULL; component = component-
>NextSiblingElement())
    {

        TiXmlElement* implementations = component->FirstChildElement("Implementations");
        if (implementations==NULL)
            return;

        TiXmlElement* current = implementations->FirstChildElement("Current");
        if (current==NULL)
            return;

        TiXmlElement* failureData = current->FirstChildElement("FailureData");
        if (failureData==NULL)
            return;

        TiXmlElement* componentFailureRate = failureData->FirstChildElement("ComponentFailureRate");

        const char * fr= componentFailureRate->GetText();

        totalFailureRate+= atof(fr);
```

```
       }

}

void getSMs(){

       //load the xml Document
       TiXmlDocument doc;
       if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
              cerr << doc.ErrorDesc() << endl;

       TiXmlHandle docHandle( &doc );

       //Doc holds all data
       TiXmlElement* model = docHandle.FirstChild("Model").Element();
       if(model == NULL)
       {
              cerr << "Failed to load file: No root element." << endl;
              exit(0);
       }


       TiXmlElement* components =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();


       for(TiXmlElement* component = components->FirstChildElement("Component"); component; component = component-
>NextSiblingElement())
       {

              TiXmlElement* name = component->FirstChildElement("Name");
              if (name==NULL)
                     return;
```

```
        TiXmlElement* failureData = component->FirstChildElement("Implementations")->FirstChildElement("Current")-
>FirstChildElement("FailureData");
        if (failureData==NULL)
            return;

        TiXmlElement* basicEvents = failureData->FirstChildElement("BasicEvents");
        if (basicEvents==NULL)
            return;

        string compName=name->GetText();

for(TiXmlElement* basicEvent = basicEvents->FirstChildElement("BasicEvent"); basicEvent; basicEvent = basicEvent-
>NextSiblingElement()){

                if (basicEvent==NULL)
                    return;

                TiXmlElement* aux = basicEvent->FirstChildElement("Name");
                if (aux==NULL)
                    return;

                string beName=aux->GetText();

                if(beName.find ("SM")!=-1){

                    SMs[smCount]+=beName;
                    //SMs.push_back(beName);
                    SMsName[smCount]+=compName;
                    //SMsName.push_back(compName);
                    smCount+=1;

                }
            }

    }

}
```

```
double checkIfCovered(string compName){

    //load the xml Document
    TiXmlDocument doc;
    if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
        cerr << doc.ErrorDesc() << endl;

    TiXmlHandle docHandle( &doc );

    //Doc holds all data
    TiXmlElement* model = docHandle.FirstChild("Model").Element();
    if(model == NULL)
    {
        cerr << "Failed to load file: No root element." << endl;
        exit(0);
    }


    TiXmlElement* components =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();
    for(TiXmlElement* component = components->FirstChildElement("Component"); component; component = component-
>NextSiblingElement()){


            TiXmlElement* aux = component->FirstChildElement("Name");

            const char * aux1= aux->GetText();
            string Name=aux1;

            for(int i=0; i<smCount; i++){

                if(Name==SMsName[i]){
                    TiXmlElement* diagnosticCoverage = component->FirstChildElement("Implementations")->FirstChildElement("Current")->FirstChildElement("FailureData")->FirstChildElement("DiagnosticCoverages")->FirstChildElement("DiagnosticCoverage");
                    if (diagnosticCoverage){


                        TiXmlElement* aux = diagnosticCoverage->FirstChildElement("Name");
                        aux1= aux->GetText();
                        string dcName=aux1;

                        if((dcName.find (compName))!=std::string::npos){

                            TiXmlElement* aux = diagnosticCoverage->FirstChildElement("SafetyGoalCoverages")->FirstChildElement("SafetyGoalCoverage")->FirstChildElement("DCSingle");
                            const char * dcSingle= aux->GetText();

                            return atof(dcSingle);

                        }

                    }

                }


            }

    }
}

string checkIfFailureModeCovered(string compName){

    //load the xml Document
    TiXmlDocument doc;
    if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
        cerr << doc.ErrorDesc() << endl;

    TiXmlHandle docHandle( &doc );
    //Doc holds all data
    TiXmlElement* model = docHandle.FirstChild("Model").Element();
    if(model == NULL)
    {
        cerr << "Failed to load file: No root element." << endl;
        exit(0);
    }


    TiXmlElement* components =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();
    for(TiXmlElement* component = components->FirstChildElement("Component"); component; component = component-
>NextSiblingElement()){

            TiXmlElement* aux = component->FirstChildElement("Name");

            const char * aux1= aux->GetText();
            string Name=aux1;

            for(int i=0; i<smCount; ++i){
                //check if component is Safety Mechanism
                if(Name==SMsName[i]){

                    TiXmlElement* diagnosticCoverage = component->FirstChildElement("Implementations")-
>FirstChildElement("Current")->FirstChildElement("FailureData")->FirstChildElement("DiagnosticCoverages")-
>FirstChildElement("DiagnosticCoverage");
                    if (diagnosticCoverage){


                        TiXmlElement* aux = diagnosticCoverage->FirstChildElement("Name");
                        aux1= aux->GetText();
                        string dcName=aux1;

                        if((dcName.find (compName))!=std::string::npos)
                            return SMs[i];
                        else if((dcName.find (compName))==std::string::npos)
                            return "none";
                    }

                }


            }

    }
}


double getLatent(string compName){

    //load the xml Document
    TiXmlDocument doc;
    if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
        cerr << doc.ErrorDesc() << endl;

    TiXmlHandle docHandle( &doc );

    //Doc holds all data
    TiXmlElement* model = docHandle.FirstChild("Model").Element();
    if(model == NULL)
    {
        cerr << "Failed to load file: No root element." << endl;
        exit(0);
    }


    TiXmlElement*                                  components                                   =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();
    for(TiXmlElement*   component   =   components->FirstChildElement("Component");   component;   component   =   component-
>NextSiblingElement()){
```

```
            TiXmlElement* aux = component->FirstChildElement("Name");

            const char * aux1= aux->GetText();
            string Name=aux1;

            for(int i=0; i<smCount; i++){

                if(Name==SMsName[i]){

                    TiXmlElement*      diagnosticCoverage      =      component->FirstChildElement("Implementations")-
>FirstChildElement("Current")->FirstChildElement("FailureData")->FirstChildElement("DiagnosticCoverages")-
>FirstChildElement("DiagnosticCoverage");
                    if (diagnosticCoverage){


                        TiXmlElement* aux = diagnosticCoverage->FirstChildElement("Name");
                        aux1= aux->GetText();
                        string dcName=aux1;

                        if((dcName.find (compName))!=std::string::npos){

                            TiXmlElement*   aux   =   diagnosticCoverage->FirstChildElement("SafetyGoalCoverages")-
>FirstChildElement("SafetyGoalCoverage")->FirstChildElement("DCLatent");
                            const char * dcLatent= aux->GetText();

                            return atof(dcLatent);

                        }

                    }

                }


            }

    }
```

```
}

void getMetrics(){

       //load the xml Document
       TiXmlDocument doc;
       if(!doc.LoadFile("ISO26262_uc_model_V4.xml"))
              cerr << doc.ErrorDesc() << endl;

       TiXmlHandle docHandle( &doc );

       //Doc holds all data
       TiXmlElement* model = docHandle.FirstChild("Model").Element();
       if(model == NULL)
       {
              cerr << "Failed to load file: No root element." << endl;
              exit(0);
       }


       TiXmlElement*                                                    components                                                    =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();


       for(TiXmlElement*    component    =    components->FirstChildElement("Component");    component;    component    =    component-
>NextSiblingElement())
       {


              TiXmlElement* compName1 = component->FirstChildElement("Name");


              const char * compName2= compName1->GetText();
              string compName=compName2;
```

```
		TiXmlElement*	failureData	=	component->FirstChildElement("Implementations")->FirstChildElement("Current")->FirstChildElement("FailureData");
		if (failureData){


			TiXmlElement*		outputDeviation		=		failureData->FirstChildElement("OutputDeviations")->FirstChildElement("OutputDeviation");

			if (outputDeviation){

				TiXmlElement*		failureLogic		=		failureData->FirstChildElement("OutputDeviations")->FirstChildElement("OutputDeviation")->FirstChildElement("Causes")->FirstChildElement("Cause")->FirstChildElement("FailureLogic");


				const char * fl= failureLogic->GetText();
				string check=fl;



				//Check if it is Residual, Single point or Latent point failure and calculate metrics

				//Single-Point-----------------------------------------------------------------------------------
				if(check.find ("AND")==-1){
					//isSPF=1;

					TiXmlElement* basicEvents = failureData->FirstChildElement("BasicEvents");

					for(TiXmlElement* basicEvent = basicEvents->FirstChildElement("BasicEvent"); basicEvent; basicEvent = basicEvent->NextSiblingElement()){


						TiXmlElement* unavailabilityFormula = basicEvent->FirstChildElement("UnavailabilityFormula");
						if (unavailabilityFormula){

							TiXmlElement*  failureRate  =  basicEvent->FirstChildElement("UnavailabilityFormula")->FirstChildElement("Constant")->FirstChildElement("FailureRate");
							if (failureRate){
```

```
                                                       const char * fr= failureRate->GetText();

                                                       double dcSingle=checkIfCovered(compName);

                                                       if(dcSingle>0 && dcSingle<1)      {
                                                              SPMetric+= atof(fr) * (1-dcSingle);

                                                              //Latent for Residual
                                                              double dcLatent=getLatent(compName);
                                                              double n= atof(fr) * (1-dcSingle);
                                                              LPMetric+= ((atof(fr))-n)*(1-dcLatent);

                                                       }


                                                       else if(dcSingle!=NULL && !(dcSingle>0 && dcSingle<=1))
                                                              SPMetric+= atof(fr);


                                                }

                                         }

                                  }

                           }

                           //Latent -------------------------------------------------------------------------------
                           else if(check.find ("AND")!=-1 && check.find ("external")!=-1){
                           //isSPF=1;

                                  TiXmlElement* basicEvents = failureData->FirstChildElement("BasicEvents");

                                  for(TiXmlElement* basicEvent = basicEvents->FirstChildElement("BasicEvent"); basicEvent; basicEvent
= basicEvent->NextSiblingElement()){

                                         TiXmlElement* aux = basicEvent->FirstChildElement("Name");
```

```
                        const char * aux1= aux->GetText();
                        string Name=aux1;

                        if(Name.find("SM")!=0){
                            TiXmlElement*        unavailabilityFormula        =        basicEvent-
>FirstChildElement("UnavailabilityFormula");
                            if (unavailabilityFormula){

                                TiXmlElement*        failureRate        =        basicEvent-
>FirstChildElement("UnavailabilityFormula")->FirstChildElement("Constant")->FirstChildElement("FailureRate");
                                if (failureRate){
                                    const char * fr= failureRate->GetText();
                                    LPMetric+= atof(fr);

                                }
                            }
                        }
                    }

                }


            }

        }
    }

}


void saveToExcel(){

    //LinkEndChild is the simplest method to insert children
    TiXmlDocument doc;

    TiXmlDeclaration * decl = new TiXmlDeclaration( "1.0", "", "" );
    doc.LinkEndChild(decl);
```

```
TiXmlElement* root = new TiXmlElement("Workbook");
doc.LinkEndChild(root);
root->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:spreadsheet");
root->SetAttribute("xmlns:o", "urn:schemas-microsoft-com:office:office");
root->SetAttribute("xmlns:x", "urn:schemas-microsoft-com:office:excel");
root->SetAttribute("xmlns:ss", "urn:schemas-microsoft-com:office:spreadsheet");
root->SetAttribute("xmlns:html", "http://www.w3.org/TR/REC-html40");

TiXmlElement* docProperties = new TiXmlElement("DocumentProperties");
docProperties->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:office");
root->LinkEndChild(docProperties);

TiXmlElement* officeDocProperties = new TiXmlElement("OfficeDocumentSettings");
officeDocProperties->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:office");
root->LinkEndChild(officeDocProperties);

TiXmlElement* excelWorkbook = new TiXmlElement("ExcelWorkbook");
excelWorkbook->SetAttribute("xmlns", "urn:schemas-microsoft-com:office:excel");
root->LinkEndChild(excelWorkbook);


//Style of the Excel Workbook
TiXmlElement* styles = new TiXmlElement("Styles");
root->LinkEndChild(styles);

TiXmlElement* style = new TiXmlElement("Style");
style->SetAttribute("ss:ID", "Default");
style->SetAttribute("ss:Name", "Normal");
styles->LinkEndChild(style);

TiXmlElement* alignment = new TiXmlElement("Alignment");
alignment->SetAttribute("ss:Vertical", "Bottom");
alignment->SetAttribute("ss:WrapText", "1");
style->LinkEndChild(alignment);

TiXmlElement* borders = new TiXmlElement("Borders");
style->LinkEndChild(borders);
```

```
TiXmlElement* font = new TiXmlElement("Font");
font->SetAttribute("ss:FontName", "Calibri");
font->SetAttribute("x:Family", "Swiss");
font->SetAttribute("ss:Size", "11");
font->SetAttribute("ss:Color", "#000000");
style->LinkEndChild(font);

TiXmlElement* interior = new TiXmlElement("Interior");
style->LinkEndChild(interior);

TiXmlElement* number = new TiXmlElement("NumberFormat");
style->LinkEndChild(number);

TiXmlElement* protection = new TiXmlElement("Protection");
style->LinkEndChild(protection);

//------------------------------------------------------------------

//Worksheet

TiXmlElement* worksheet = new TiXmlElement("Worksheet");
worksheet->SetAttribute("ss:Name", "Sheet1");
root->LinkEndChild(worksheet);

TiXmlElement* table = new TiXmlElement("Table");
table->SetAttribute("ss:ExpandedColumnCount", "12");
table->SetAttribute("ss:ExpandedRowCount", "30");
//table->SetAttribute("x:FullColumns", "10");
//table->SetAttribute("x:FullRows", "20");
//table->SetAttribute("ss:DefaultRowHeight", "15");

worksheet->LinkEndChild(table);


TiXmlElement* row = new TiXmlElement("Row");
table->LinkEndChild(row);

TiXmlElement* cell = new TiXmlElement("Cell");
```

```
row->LinkEndChild(cell);
TiXmlElement* data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Component" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Failure Rate" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Failure Mode" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Failure Mode Failure Rate" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Safety Mechanism preventing safety goal violation?" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
```

```
data->LinkEndChild( new TiXmlText( "Failure Mode Coverage" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Residual/Single-point fault Failure Rate" ));
cell->LinkEndChild(data);

/*
cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Safety Mechanism preventing safety goal violation, in combination with other fault?" ));
cell->LinkEndChild(data);
*/

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Failure Mode Coverage in respect to Latent Faults" ));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText( "Latent-Point Fault Failure Rate" ));
cell->LinkEndChild(data);


//Go through all the components-------------------------------------------------------

//load the xml Document
TiXmlDocument doc1;
```

```
	if(!doc1.LoadFile("ISO26262_uc_model_V4.xml"))
		cerr << doc1.ErrorDesc() << endl;

	TiXmlHandle docHandle( &doc1);

	//Doc holds all data
	TiXmlElement* model = docHandle.FirstChild("Model").Element();
	if(model == NULL)
	{
		cerr << "Failed to load file: No root element." << endl;
		exit(0);
	}


	TiXmlElement*                                                   components                                                   =
docHandle.FirstChild("Model").FirstChild("Perspectives").FirstChild("Perspective").FirstChild("System").FirstChild("Components").Eleme
nt();


	for(TiXmlElement*    component    =    components->FirstChildElement("Component");    component;    component    =    component-
>NextSiblingElement())
	{
		//Component Name

		TiXmlElement* row = new TiXmlElement("Row");
		table->LinkEndChild(row);

		TiXmlElement* compName1 = component->FirstChildElement("Name");
		const char * compName2= compName1->GetText();
		string compName=compName2;

		cell = new TiXmlElement("Cell");
		row->LinkEndChild(cell);
		data = new TiXmlElement("Data");
		data->SetAttribute("ss:Type", "String");
		data->LinkEndChild( new TiXmlText(compName));
		cell->LinkEndChild(data);
```

```
        TiXmlElement*      failureData      =      component->FirstChildElement("Implementations")->FirstChildElement("Current")-
>FirstChildElement("FailureData");
        if (failureData){
            TiXmlElement* failureRate=failureData->FirstChildElement("ComponentFailureRate");
            const char * aux= failureRate->GetText();
            string fr=aux;

            cell = new TiXmlElement("Cell");
            row->LinkEndChild(cell);
            data = new TiXmlElement("Data");
            data->SetAttribute("ss:Type", "String");
            data->LinkEndChild( new TiXmlText(fr));
            cell->LinkEndChild(data);

            TiXmlElement*          outputDeviation           =           failureData->FirstChildElement("OutputDeviations")-
>FirstChildElement("OutputDeviation");

            if (outputDeviation){

                TiXmlElement*          failureLogic           =           failureData->FirstChildElement("OutputDeviations")-
>FirstChildElement("OutputDeviation")->FirstChildElement("Causes")->FirstChildElement("Cause")->FirstChildElement("FailureLogic");


                const char * fl= failureLogic->GetText();
                string check=fl;


            TiXmlElement* basicEvents=failureData->FirstChildElement("BasicEvents");
            int n=0;
            for(TiXmlElement* basicEvent = basicEvents->FirstChildElement("BasicEvent"); basicEvent; basicEvent = basicEvent-
>NextSiblingElement())
            {

                n++;
                TiXmlElement* aux = basicEvent->FirstChildElement("Name");
                string beName=aux->GetText();
                TiXmlElement* unavailabilityFormula = basicEvent->FirstChildElement("UnavailabilityFormula");
```

```
                            if(unavailabilityFormula){
                                   TiXmlElement*          aux1          =          unavailabilityFormula->FirstChildElement("Constant")-
>FirstChildElement("FailureRate");
                                   const char * fr1=aux1->GetText();
                                   string fr=aux1->GetText();

                                   std::size_t found = beName.find("SM");
                                   if(found==std::string::npos){

                                          //If the Component has more than 1 relevant Failure Mode
                                          if(n>=2){
                                                 int t=n;
                                                 TiXmlElement* row = new TiXmlElement("Row");
                                                 table->LinkEndChild(row);

                                                 while (t>0){

                                                        cell = new TiXmlElement("Cell");
                                                        row->LinkEndChild(cell);
                                                        t--;
                                                 }

                                                 //Failure Mode
                                                 cell = new TiXmlElement("Cell");
                                                 row->LinkEndChild(cell);
                                                 data = new TiXmlElement("Data");
                                                 data->SetAttribute("ss:Type", "String");
                                                 data->LinkEndChild( new TiXmlText(beName));
                                                 cell->LinkEndChild(data);

                                                 //Failure Mode Failure Rate
                                                 cell = new TiXmlElement("Cell");
                                                 row->LinkEndChild(cell);
                                                 data = new TiXmlElement("Data");
                                                 data->SetAttribute("ss:Type", "String");
                                                 data->LinkEndChild( new TiXmlText(fr));
                                                 cell->LinkEndChild(data);
```

```
string sm = checkIfFailureModeCovered(compName);
double dcSingle=checkIfCovered(compName);
double dcLatent=getLatent(compName);


//Check if it is Residual, Single point or Latent point failure (DC is < 100%)---Example:T71

if(check.find ("AND")==-1){

    //Residual (has DC) and Latent (if DC Single-Point <100%)
    if(dcSingle>0 && dcSingle<1){


        //Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(sm));
        cell->LinkEndChild(data);

        //Diagnostic Coverage for SPF
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcSingle)));
        cell->LinkEndChild(data);

        //SPF Metric
        double SPF=atof(fr1)*(1-dcSingle);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(SPF)));
        cell->LinkEndChild(data);
        //Perceived Faults
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcLatent)));
        cell->LinkEndChild(data);

        //Latent-Point Failure Metric
        double LPF=((atof(fr1))-SPF)*(1-dcLatent);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(LPF)));
        cell->LinkEndChild(data);
}


//Single-Point Failure with no DC
else if(dcSingle!=NULL && !(dcSingle>0 && dcSingle<=1)){

        //No Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText("none"));
        cell->LinkEndChild(data);

        //Diagnostic Coverage is 0
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText("0"));
        cell->LinkEndChild(data);
```

```
                //SPF Metric (just the Failure Rate of the Component)
                double SPF=atof(fr1);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                data = new TiXmlElement("Data");
                data->SetAttribute("ss:Type", "String");
                data->LinkEndChild( new TiXmlText(to_string(SPF)));
                cell->LinkEndChild(data);

                //No Latent Fault Diagnostic Coverage
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

                //No LPF Metric
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

        }

        //Component Fault that is not relevant for the Violation of the Safety goal
        else {
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

        }
}

//Only Latent with combination of failures
else if(check.find ("AND")!=-1 && check.find ("external")!=-1){
```

```
                //No Safety Mechanism
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

                //No Single-Point Coverage
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

                //No Single-Point Failure Metric
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

                //Coverage for Latent Faults is 0
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                data = new TiXmlElement("Data");
                data->SetAttribute("ss:Type", "String");
                data->LinkEndChild( new TiXmlText("0"));
                cell->LinkEndChild(data);

                //Latent-Point Failure: Component AND external condition
                double LPF=atof(fr1);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                data = new TiXmlElement("Data");
                data->SetAttribute("ss:Type", "String");
                data->LinkEndChild( new TiXmlText(to_string(LPF)));
                cell->LinkEndChild(data);


        }
}

//If the Component has just 1 relevant Failure Mode
else if (n<2){

        //Failure Mode
        cell = new TiXmlElement("Cell");
```

```
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText(beName));
cell->LinkEndChild(data);

//Failure Mode Failure Rate
cell = new TiXmlElement("Cell");
row->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText(fr));
cell->LinkEndChild(data);

string sm = checkIfFailureModeCovered(compName);
double dcSingle=checkIfCovered(compName);
double dcLatent=getLatent(compName);


//Check  if  it  is  Residual,  Single  point  or  Latent  point  failure  (DC  is  <  100%)---
```

Example:T71

```
if(check.find ("AND")==-1){

    //Residual (has DC) and Latent (if DC Single-Point <100%)
    if(dcSingle>0 && dcSingle<1){


        //Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(sm));
        cell->LinkEndChild(data);

        //Diagnostic Coverage for SPF
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcSingle)));
        cell->LinkEndChild(data);

        //SPF Metric
        double SPF=atof(fr1)*(1-dcSingle);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(SPF)));
        cell->LinkEndChild(data);

        //Perceived Faults
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(dcLatent)));
        cell->LinkEndChild(data);

        //Latent-Point Failure Metric
        double LPF=((atof(fr1))-SPF)*(1-dcLatent);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(LPF)));
        cell->LinkEndChild(data);
}


//Single-Point Failure with no DC
else if(dcSingle!=NULL && !(dcSingle>0 && dcSingle<=1)){

        //No Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText("none"));
        cell->LinkEndChild(data);

        //Diagnostic Coverage is 0
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText("0"));
        cell->LinkEndChild(data);

        //SPF Metric (just the Failure Rate of the Component)
        double SPF=atof(fr1);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(to_string(SPF)));
        cell->LinkEndChild(data);

        //No Latent Fault Diagnostic Coverage
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);

        //No LPF Metric
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);

}

//Component Fault that is not relevant for the Violation of the Safety goal
else {
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        cell = new TiXmlElement("Cell");
```

```
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);
                cell = new TiXmlElement("Cell");
                row->LinkEndChild(cell);

        }
}

//Only Latent with combination of failures
else if(check.find ("AND")!=-1 && check.find ("external")!=-1){

        //No Safety Mechanism
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);

        //No Single-Point Coverage
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);

        //No Single-Point Failure Metric
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);

        //Coverage for Latent Faults is 0
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText("0"));
        cell->LinkEndChild(data);

        //Latent-Point Failure: Component AND external condition
        double LPF=atof(fr1);
        cell = new TiXmlElement("Cell");
        row->LinkEndChild(cell);
```

```
                            data = new TiXmlElement("Data");
                            data->SetAttribute("ss:Type", "String");
                            data->LinkEndChild( new TiXmlText(to_string(LPF)));
                            cell->LinkEndChild(data);


                        }

                    }


                }


            }




        }
        n=0;


        }


    }



}

//Total Residual+Single Failure Rates and Latent Failure Rate
getMetrics();
string sp=to_string(SPMetric);
string lp=to_string(LPMetric);

TiXmlElement* row1 = new TiXmlElement("Row");
```

```
table->LinkEndChild(row1);

TiXmlElement* row2 = new TiXmlElement("Row");
table->LinkEndChild(row2);

cell = new TiXmlElement("Cell");
row2->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText("TOTAL METRICS"));
cell->LinkEndChild(data);


for (int i=0; i<5; i++){
       cell = new TiXmlElement("Cell");
       row2->LinkEndChild(cell);
}

//residual and single-point Failure Total Failure Rate----------------------------
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText(sp));
cell->LinkEndChild(data);

cell = new TiXmlElement("Cell");
row2->LinkEndChild(cell);

//Latent-Point Failure Total Failure Rate-------------------------------------------
cell = new TiXmlElement("Cell");
row2->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText(lp));
cell->LinkEndChild(data);

//Metrics--------------------------------------------------------------------------
GetTotalFailureRate();
string fr=to_string(totalFailureRate);
```

```
TiXmlElement* row3 = new TiXmlElement("Row");
table->LinkEndChild(row3);

TiXmlElement* row4 = new TiXmlElement("Row");
table->LinkEndChild(row4);

//Single-Point Metric
cell = new TiXmlElement("Cell");
row4->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText("Single-Point Metric"));
cell->LinkEndChild(data);

double SPM=1-(SPMetric/totalFailureRate);
string spMetric=to_string(SPM);
cell = new TiXmlElement("Cell");
row4->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText(spMetric));
cell->LinkEndChild(data);

TiXmlElement* row5 = new TiXmlElement("Row");
table->LinkEndChild(row5);

//Latent-Point Metric
cell = new TiXmlElement("Cell");
row5->LinkEndChild(cell);
data = new TiXmlElement("Data");
data->SetAttribute("ss:Type", "String");
data->LinkEndChild( new TiXmlText("Latent-Point Metric"));
cell->LinkEndChild(data);

double LPM=1-(LPMetric/(totalFailureRate-SPMetric));
string lpMetric=to_string(LPM);
cell = new TiXmlElement("Cell");
```

```
        row5->LinkEndChild(cell);
        data = new TiXmlElement("Data");
        data->SetAttribute("ss:Type", "String");
        data->LinkEndChild( new TiXmlText(lpMetric));
        cell->LinkEndChild(data);


        //Save the document
        bool success = doc.SaveFile("excel.xml");
        //doc.Clear();

}



void main(){

        getSMs();

        saveToExcel();

}
```