NTNU – Trondheim
Norwegian University of
Science and Technology

Development and construction of car for eco-marathon for participation in competition

Verification,Validation and Testing activities
for the DNV Fuel Fighter 2

Itxaso Yuguero Garmendia

Product Design and Manufacturing
Submission date: June 2012
Supervisor: Knut Einar Aasland, IPM

Norwegian University of Science and Technology
Department of Engineering Design and Materials

Preface

This report follows the work done during the first semester of the year. The report has been done in the Department of Engineering Design and Materials (IPM) of the NTNU with Associate Professor Knut Aasland and post-doc researcher Cecilia Haskins as supervisors. The author has been on Erasmus exchange program for a year in the NTNU.

The main topic of the Thesis is the definition and development of Verification, Validation and Testing activities for the DNV Fuel Fighter 2.

The Specialization Project done during the fall semester and this Master Thesis are the first approach to Systems Engineering for the author. This project has given the writer the opportunity to discover System Engineering and to start a career out of it. The writer got a job in Aker Solution as System Engineer and she believes that it would have not been possible without the SEM project.

The writer would like to express a deep gratitude to post-doc researcher Cecilia Haskins for the enormous support, guidance and incalculable help. Her vitality and love for System Engineering is contagious. The author will also like to thank Associate Professor Knut Aasland for giving her the chance of being part of the project.

A special thanks to the SEM team, it has been a pleasure and an honor for the writer to be part of the team. The author will also like to thank Oluf Tonning, for the support and the shared ideas and vision about System Engineering and the project.

Trondheim, June 2012

Itxaso Yuguero-Garmendia

Abstract

The goal of this Thesis is to verify a winning solution for the DNV Fuel Fighter 2, the verification of the design and development will be achieved by a series of verification, validation and testing activities. The Literature review of the report represents the VVT activities during the entire life cycle. The Theory and Methods used in the Thesis are based on A. Engel's "Verification, Validation and Testing activities of Engineered Systems". The author has customized those VVT activities so they fit the time and resource constrains of the case of study.

The case is the NTNU's fifth entrance to the Shell Eco Marathon competition, The DNV Fuel Fighter 2. The actual repot is a reflection of the first time in SEM's project where an entire Thesis reflects the VVT activities in order to qualify the vehicle.

This Master Thesis follows the work that was done in the specialization project 2011 fall in the NTNU. The fall report was focused on the trade-off and requirement analysis and in the definition a high level architecture that could be use in the project. The project work was used as a foundation for the work that was done afterwards in this Master Thesis. The work done during the year is based on the systems engineering effort made from the previous year. The author along with the other system engineer of the project has upgraded the SE effort.

The main contribution of the Thesis has been the development of the VVT activities and to prove that they are useful for projects with time and resource constrains.

The suggested future work consists of continuing with the use of the VVT strategy performed this year and to upgrade it until the Acceptance stage; where the final user will be the responsible of performing the tests.

NORGES TEKNISK-
NATURVITENSKAPELIGE UNIVERSITET
INSTITUTT FOR PRODUKTUTVIKLING
OG MATERIALER

MASTEROPPGAVE VÅR 2012
FOR
STUD.TECHN. PETTER T. LARSEN,
HÅKON JOHAN SEINESS,
ITXASO YUGUERO GARMENDIA,
HANS GUDVANGEN OG
ASLAK ESPELAND

UTVIKLING OG BYGGING AV BIL FOR DELTAKELSE I ECO-MARATHON-KONKURRANSEN
Development and construction of car for eco-marathon for participation in competition

I høstsemesteret har prosjektgruppa gjort en spesifikasjon av en ny Eco-marathon-bil, basert på undersøkelse av fjorårets Eco-marathon-bil og de nye reglene og rammebetingelsene for 2012. De første fasene av et prosjekt fram mot en ny bil er dermed gjennomført. Nå skal de gjenstående fasene fram mot et kjøretøy som skal delta i Shell Eco-marathon i Nederland i mai 2012 gjennomføres. Et godt grunnlag er lagt, og masteroppgaven bygger på resultatene fra prosjektoppgaven.

Arbeidet i masteroppgaven foregår på fire nivå:

- Prosjektet i sin helhet inklusive offentlighetsarbeid, prosjektstyring og sponsorarbeid
- Selve bilen som et samspill av alle sine enkeltsystemer
- Enkeltsystemene med tilhørende interface
- Nødvendige eksterne tekniske og organisatoriske støttesystemer knyttet til bygging, testing og gjennomføring

Alt må selvsagt gjøres innenfor reglene som gjelder for Eco-marathon. Kandidaten må bidra på tvers av alle 4 nivå og samtidig ta et helhetlig ansvar for definerte deloppgaver som må defineres i prosjektplanen.

Arbeidet bedømmes både med hensyn til helheten og med hensyn til kandidatens deloppgaver. Bedømmelsen tar hensyn til både sluttresultatene og dokumentasjonen i utviklingsarbeidet. Dette aspektet er spesielt viktig med hensyn til fremtidig deltakelse i Eco-marathon. Det presiseres at det er kjempebra å "vinne", men det er hverken tilstrekelig eller nødvendig for en god bedømmelse.

Leveransen fra prosjektet er i henhold til det fire nivå:

- Prosjektrapport inklusive informasjonsmateriell som er utviklet
- Selve bilen samt teknisk produktutviklingsrapport inklusive evaluering og forbedringsforslag
- Hvert enkeltsystem samt teknisk produktutviklingsrapport inklusive evaluering og forbedringsforslag
- Alle tekniske og organisatoriske støttesystemer samt utviklingsrapport inklusive evaluering og forbedringsforslag

Besvarelsen skal ha med signert oppgavetekst, og redigeres mest mulig som en forskningsrapport med et sammendrag på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse, etc. Ved utarbeidelse av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelse legges det stor vekt på at resultater er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

Som et vedlegg til rapporten skal det leveres en PU-journal. Denne skal være uredigert og inneholde alle de notater og idéer man har vært inne på undervegs i arbeidet. Fortrinnsvis skal den være i instituttets A3-format.

Senest 3 uker etter oppgavestart skal et A3 ark som illustrerer arbeidet leveres inn. En mal for dette arket finnes på instituttets hjemmeside under menyen undervisning. Arket skal også oppdateres ved innlevering av masteroppgaven.

Besvarelsen skal leveres i elektronisk format via DAIM, NTNUs system for Digital arkivering og innlevering av masteroppgaver.

Kontaktperson hos AS Norske Shell: Lillian Aasheim
Kontaktperson hos DNV: Kristina Dahlberg
Ressurspersoner ved NTNU/SINTEF: Nils Petter Vedvik, Terje Rølvåg, Detlef Blankenburg

Torgeir Welo
Instituttleder

Knut Aasland
Faglærer

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

Table of Contents

1. Introduction 1
2. SE Theory and Methods 2
   - 2.1 Role of System Engineer 3
   - 2.2 System Life-Cycle 5
     - 2.2.1 SE Vee 9
     - 2.2.2 Risk analysis and management 13
     - 2.2.3 VVT Methods: Testing 18
     - 2.2.4 VVT activities during definition 21
     - 2.2.5 VVT activities during design 22
     - 2.2.6 VVT activities during implementation 23
     - 2.2.7 VVT activities during integration 24
     - 2.2.8 VVT activities during qualification 25
3. Empirical Results 27
   - 3.1 DNV Fuel Fighter 2: Life cycle 27
     - 3.1.1 Introduction: 27
     - 3.1.2 Visualizing the life cycle: 29
     - 3.1.3 Life cycle processes 31
     - 3.1.4 Role of SE inside the DNV FF2 31
     - 3.1.5 Risk analysis and management 34
   - 3.2 Validation, Verification and Testing activities of the DNV FF 2. 36
     - 3.2.1 Unit Testing: 37
     - 3.2.2 Assembly Test: 38
     - 3.2.3 Performance Test: 44
     - 3.2.4 Rotterdam 46
4. Discussion 53
5. Conclusion 56

References 57

Appendix I: Requirement Allocation i

Appendix II: Architectural design ii

Appendix III: Risk Management iii

Appendix IV: Mitigation plan v
Appendix V: Assembly test vi
System Integration test Report SysTR: Mechanical Parts vi
System Integration Test Description: SysTD vii
Appendix VI: Performance test xi
System Qualification/Acceptance test report. xi
System Qualification/ Acceptance Test Description. SysTD xii
Appendix VII: Acceptance test review xiv

List of Figures

Figure 1 System Life-cycle Processes Overview per ISO/IEC 15288:2008 [11] 6
Figure 2 Principal stages in a life cycle.[12] 7
Figure 3 Evolution of System Materialization through the System Life Cycle.[13] 8
Figure 4 SE Vee model [15] 9
Figure 5 DoD Risk Management Process[22] 13
Figure 6 Risk cube display 14
Figure 7 Evaluation of consequences[24] 15
Figure 8 Evaluation of likelihood[25] 15
Figure 9 Variation of program risk and effort throughout system development.[27] 16
Figure 10 Fundamental System Testing Process[30] 18
Figure 11 Hierarchical testing: white or black - box testing.[31] 20
Figure 12 Example of Requirement Verification Matrix[32] 21
Figure 13 System Life cycle [33] 23
Figure 14 Vee model for the DNV Fuel Fighter 2[36] 27
Figure 15 WBS that could be found at SEM's office 29
Figure 16 Visual representation of the color code.[39] 32
Figure 17 Board that can be found at SEM's workshop 33
Figure 18 Bottom-up integration 38
Figure 19 Rear Suspension subsystem 39
Figure 20 SEM team measuring the distance to perform the visibility check 41
Figure 21 Detail of how the speed was measured. 42
Figure 22 Test day at Dragvoll's parking lot. 42
Figure 23 Gylling's battery packs 43
Figure 24 Altitec's battery pack 44
Figure 25 Performance test at Dragvoll's parking lot 45
Figure 26 Shell Marshals checking the fire extinguisher 47
Figure 27 Checking the dimensions 47
Figure 28 Race Track Ahoy Rotterdam 48
Figure 29 Piece from the Front Suspension that bent. 50
Figure 30 Finishing the first valid attempt 51
Figure 31 Front-left part of the car after the accident 52

Abbreviations

NTNU	*Norges Teknisk Naturvitenskapelige Universitet*
SEM	Shell Eco Marathon
DNV	Det Norske Veritas
DNVFF	DNV Fuel Fighter
SE	System Engineer/ System Engineering
VVT	Verification, Validation and Testing
IPT	Integrated Product Team
DoD	Department of Defense
SUT	System Under Test
RVM	Requirement Verification Matrix
SysTD	System Test Description
SysTR	System Test Report
BE	Battery Electric
FC	Fuel Cell
WBS	Work breakdown structure
V&V	Verification and Validation
PM	Project Manager
UC	Urban Concept
BMS	Battery Management System
UC	Urban Concept
PR	Public Relations

1. Introduction

The introduction will serve as a clear and quick presentation of the work performed in the Thesis and also will help to understand why that work was done in such a way.

In the Master Thesis description the author is together with the mechanical team members. The writer decided that it was a better choice to deliver a separated report to go more in detail about the SE work that has been done for the DNV Fuel Fighter 2.

To have a better insight into the Thesis, the background of the project will be introduced. This year it has been NTNU's fifth entrance to the Shell Eco-Marathon competition (SEM). The results that NTNU's teams have achieved in this competition are outstanding, even having a world-record breaking car in 2009. All these achievements were accomplishes in the Urban Concept Fuel Cell class.

The competition will be held in Rotterdam in a street track for the first time in SEM Europe's history. As a result of these new conditions the SEM 2012 team decided to build a whole new car to be able to adapt to the new conditions. The 2012 team also decided to take part in the Battery electric class instead of the Fuel cell. A deeper explanation of why these changes were done and what was the outcome will be explained throughout the Thesis.

The System Engineering effort has also change from previous years. The DNV Fuel Fighter 2011 was the first team where Systems Engineering was introduced and the SE involvement was proved to be really successful. Since last year, the Systems Engineering contribution to the team has been in continuous increase. The DNVFF 2 has gone one step forward and has had the involvement of two systems engineers. The main SE effort was on designing and performing a testing procedure and also in transferring the knowledge to future SEM teams. The SE effort was focused on these two main topics since the team saw the need of improvement based on project status. SE's foundation is on analyzing a project needs and adapting the effort to cover that need.

The scope of this Thesis is found on the Verification, Validation and Testing activities designed and performed to qualify the DNV Fuel Fighter 2. However, SE work covered a wider range of activities from encouraging communication within the team to the development of a risk management process. The fact that this year the whole car is new made the VVT activities of great importance since their goal is to make sure that the product is delivered as error free as possible, apart from being successfully operational and meeting user's needs.

The SE work that is presented in this Thesis is divided into two parts. The first part will cover the Theory and Methods upon which the work is based. Once the theoretical background of the work done has been explained and the reader has understanding of what that means the Empirical results will be presented. The Empirical results will show the reader the work that was done during the second semester of the year, which is based on the specialization project that was done for the fall semester.

2. SE Theory and Methods

This section will explain the literature basis of the whole Master Thesis. The work done in the thesis is based on the "Verification, Validation and Testing of Engineered Systems" by A. Engel.

This whole Thesis, as said before, is a reflection of the SE work done in the DNV Fuel Fighter 2. This means that the work done is basically practical and therefore methods and theory play together. It would be not possible or too difficult to be able to separate the SE theory from the Methods in a project like the Shell Eco Marathon car. Every SE book or literature explains how SE practice should be performed both in the organization and in the project. However, not every project has the same characteristics and therefore SE practice and processes need to be tailored in order to fit the characteristic of the project. Before going more into detail some definitions that the reader should know will be introduced. According to the ISO/IEC 15288:2008[1]:

- **System:** a combination of interacting elements organized to achieve one or more stated purposes.
- **Project:** an endeavor with start and finish criteria undertaken to create a product or service in accordance with specified resources and requirements.
- **Process:** set of interrelated or interacting activities which transform inputs into outputs.
- **System Element:** a member of a set of elements that constitutes a system.

This section and the Empirical results of the Thesis will deal with Verification and Validation concepts. In order to give the reader a better understanding of what the writer understands as Verification and Validation, these concepts are defined.

According to ISO/IEC 15288:2008
The purpose of the Verification Process is to confirm that the specified design requirements are fulfilled by the system.

This process provides the information required to effect the remedial actions that correct non-conformances in the realized system or the processes that act on it. [2]

Validation refers to the confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.[3]
[ISO 9000:2005]

NOTE Validation is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives (i.e., meet stakeholder requirements) in the intended operational environment.

The VVT activities can be found throughout the system life cycle and that is the reason why the system life cycle will be explained. The life cycle will be explained from the SE point of view and the activities that a SE has to perform throughout the entire life cycle will be introduced to the reader.

2.1 Role of System Engineer

It is not easy to describe what exactly is system engineer's job or task. This difficulty is found on the fact that Systems Engineering has an extremely huge range of tasks. According to Sheard's [96][4] there are twelve different Systems Engineering roles that will be presented in the following lines.

1. **Requirement Owner Role:** Requirements Owner/requirements manager, allocator, and maintainer/specifications writer or owner/developer of functional architecture/developer of system and subsystem requirements from customer needs.
   The goal of this role is to formulate requirements in such a way that will cover stakeholders and customers' needs. These requirements will be linked to subsystems or systems that can be architected. The role will also cover the development of functional architecture that expresses correctly the functionality of the product.

2. **System Designer Role:** System Designer / owner of "system" product / chief engineer / system architect / developer of design architecture / specialty engineer (some, such as human-computer interface designers) / "keepers of the holy vision" [Boehm 94][5].
   The role of system designer interacts with the role of requirement owner since the tasks that the System Designer develops are concurrent to the ones that the Requirement Owner does. The System Designer is the responsible of developing a high level architecture and has to make sure that there are ways of building the system that meet the system requirements. Once the system specifications are met the System Designer will define the needs for the next lower system.

3. **System Analyst Role:** System Analyst/performance modeler/keeper of technical budgets/system modeler and simulator/risk modeler/specialty engineer (some, such as electromagnetic compatibility analysts).
   The System Analyst will be the person that will confirm that the design meets the requirements; system modeling will be one of her/his tasks in order to achieve this. System modeling will also help system engineers and the rest of engineers to understand the operation of the system.

4. **Validation and Verification Role:** Validation and Verification engineer / test engineer / test planner / owner of system test program / system selloff engineer.
   The SE that has this role will design and perform a verification and validation plan to make sure that the system, the way it is built meets the requirements. The SE will design test cases and procedures that will be performed in different scenarios. The questions related to performance that appear during the verification process will be answered by the SE that is the responsible of VV activities.
   In many organizations, there is a test group formed by test engineers and they are the responsible of verifying and validating a product by designing test cases and scenarios. However, in other organizations the system engineer is the responsible of the validation and verification.

5. **Logistics and operations Role:** Logistics, Operations, maintenance, and disposal engineer / developer of users' manuals and operator training materials.
   The role of Logistic and Operations consists of making sure that in the requirements the maintenance, operation and disposal phases of the life cycle are taken into account.

6. **Glue Role:** Owner of "Glue" among subsystems / system integrator / owner of internal interfaces / seeker of issues that fall "in the cracks" / risk identifier / "technical conscience of the program" [Fisher 92][6].
   This role consists of seeking problems or possible issues and solving or preventing them. In big systems, many of the problems appear in the interfaces and that is why a big concern has to be focused there.

7. **Customer Interface Role:** Customer Interface/customer advocate/customer surrogate/customer contact.
   The task of the engineer that plays this role is to represent customers' view and to check if this view has been respected along the project.

8. **Technical Manager Role:** Technical Manager / planner, scheduler, and tracker of technical tasks / owner of risk management plan / product manager / product engineer.
   The Technical Manager will take care of cost, scheduling and also maintaining support groups as IT groups. In companies this role is the one that the Project Manager will do.

9. **Information Manager Role:** When the information system becomes more complex it is important that someone has the overview of the overall information. The information manager is the person with that view.

10. **Process Engineer Role:** Process engineer/business process reengineer/business analyst/owner of the systems engineering process.
    Process Engineer will document, follow-up, own and improve the System engineering processes within the organization.

11. **Coordinator Role:** Coordinator of the disciplines / tiger team head / head of integrated product teams (IPTs) / system issue resolver.
    For this specific role leadership skills are really essential as the role consist of coordinating groups to solve problem and trying to find consensus within the project. This role can be permanent within a company or transitory. It will be permanent if discipline is what wants to be achieved and it can be transitory and be used to solve specific problems in specific times.

12. **"Classified Ads System Engineering" Role:** This role can be presented as the other. Meaning that is was classified like this as a respond to those ads that were seeking for either a system engineer with a mixture of skills from the roles mentioned before, different skill or system engineers with the experience with the other roles and expertise with computers.

2.2 System Life-Cycle

Every system has a life cycle. The life cycle covers development, production utilization and retirement stages. The life cycle is used within projects as a framework to help the project to meet stakeholders' need in the most efficient way.

The term "system life cycle" is commonly used to refer to the stepwise evolution of a new system from concept through development and on to production, operation, and ultimate disposal. [7]

According to ISO/IEC 15288:2008:

5.2.2- Life cycles vary according to the nature, purpose, use and prevailing circumstances of the system. Each stage has a distinct purpose and contribution to the whole life cycle and is conserved when planning and executing the system life cycle.[8]

Systems engineers orchestrate the development of a solution from requirements determination through operations and system retirement by assuring that domain experts are properly involved, that all advantageous opportunities are pursued, and that all significant risks are identified and mitigated. [9]

System Engineers are involved in every life cycle stage, and together with the project manager they will be the responsible of tailoring the life cycle, defining decision gates and milestones.
The definition of decision gates, formed by milestones and reviews, will allow the system to meet the stakeholders' need. The milestones are set in the project in order to keep track of the development of it. However, there is a difference between milestones and decision gates. Every decision gate is a milestone but not all milestones are decision gates. The milestones set a time of a task to be achieved while a decision gate, besides of providing that information is able to answer the following questions:

According to the SE Handbook[10]:

- Does the project deliverable still satisfy the business case?
- Is it affordable?
- Can it be delivered when needed?

Every decision gate has to be reached; skipping those increases the risk of failure as the system readiness can be jeopardized. According to the SE Handbook each decision gate can be:

- **Acceptable:** Go to the following steps of the project.
- **Acceptable with reservations:** Keep on with the project and make changes or respond to eliminate the uncertainties
- **Unacceptable:** Three different options can be done if the milestone has been defined as unacceptable. The first option is to repeat the same stage and see if it can be defined in other way. The second option is to go back to the preceding milestone and finally the last option is to put the activities of the project on hold.
- **Unsalvageable:** Finish the project nothing more will be done.

In the Empirical part of the Thesis the milestones and decision gates of the DNV FF2 will be expressed and visualized. It will also be explained how the team made the decision of relating to each decision gate one of the concepts explains above.

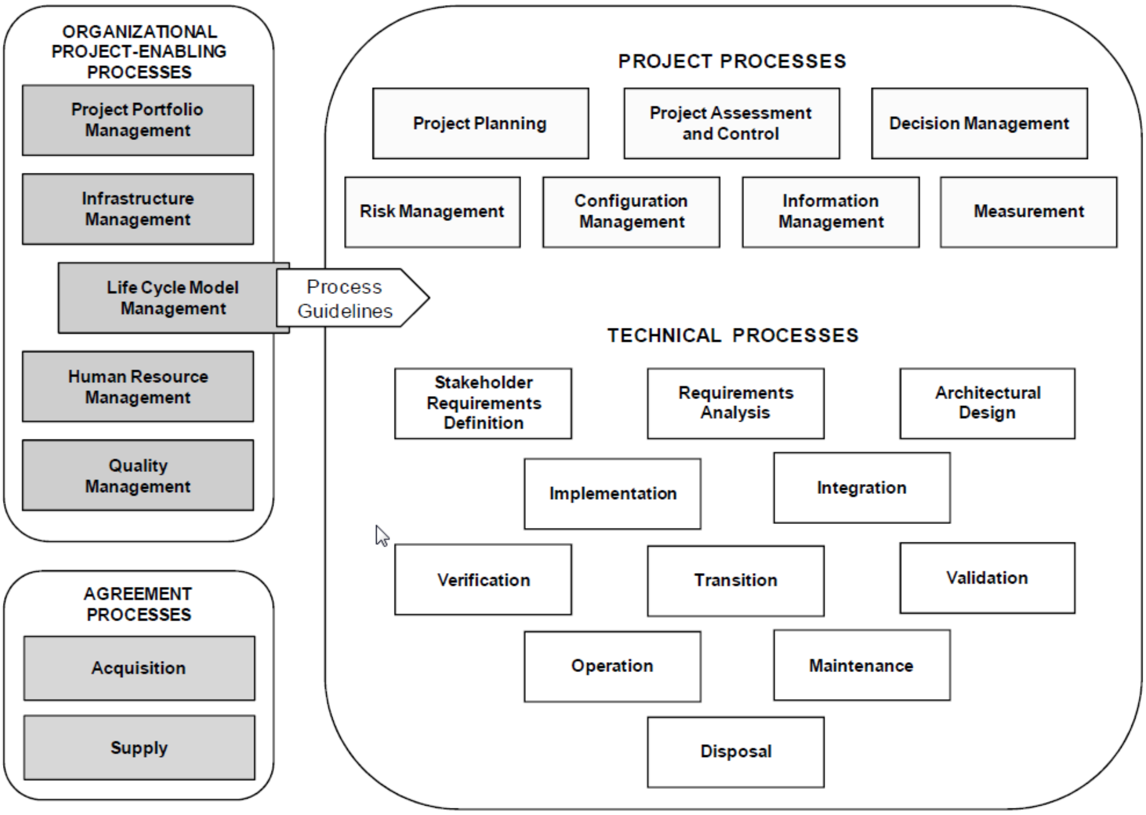


Figure 1 System Life-cycle Processes Overview per ISO/IEC 15288:2008 [11]

Figure 1 shows the 4 processes that are involved in systems life cycle according to ISO/IEC 15288:2008. Those four processes are project processes, technical processes, agreement processes and organizational project-enabling processes.

- **Project Process:** The project process covers project planning, Project assessment and control, Decision Management, Risk Management, Configuration Management, Information management and Measurements.
- **Technical Process:** The technical processes are linked to all the life cycle and they go from Stakeholder Requirements Definition to Disposal going through Requirement analysis, Architectural design, Implementation, Integration, Verification, Transition, Validation, Operation, Maintenance.
- **Agreement Process:** They cover Acquisition and Supply processes.
- **Organizational Project-Enabling Processes:** Processes that can be found here are Project Portfolio Management, Infrastructure Management, Life Cycle Model Management, human Resource Management and Quality Management.

The SE work done for the DNV FF2 covers some of these processes, such as Risk Management, Requirement analysis, Stakeholder Requirement definition, Architectural design, Implementation, Integration, Verification and Validation. Some of these processes were done during the fall semester and other during the time that the Thesis was being done. Therefore, some of the processes will be explained thoroughly in the Thesis and some other will be mentioned and referred to the specialization project.

The processes that are explained are done throughout the life cycle. Figure 2 shows the different engineering stages that are performed during the life cycle. This figure is an approach to the visualization of the life-cycle of a product. In Figure 2 the SE effort is displayed according to the different stages of the project.

The life cycle can also be divided into Concept Development, Engineering Development and Post development.

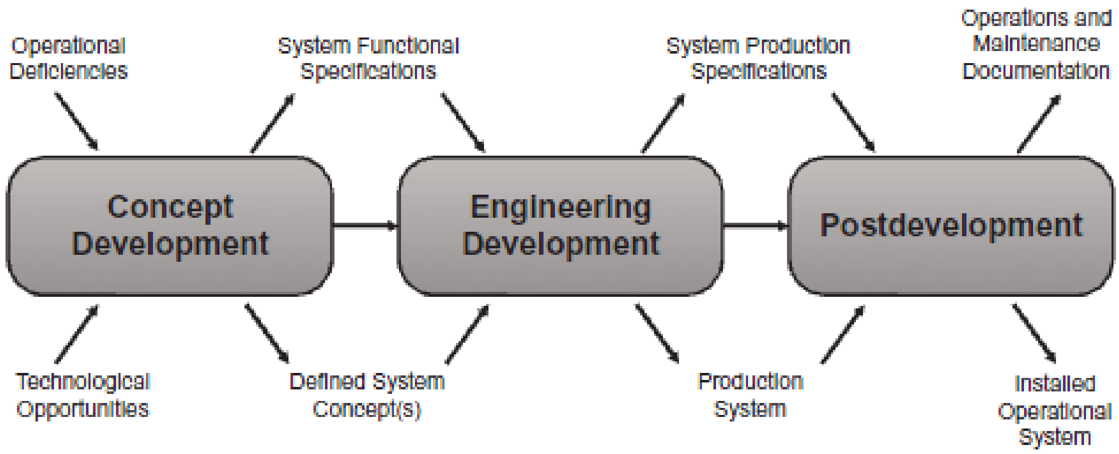


Figure 2 Principal stages in a life cycle.[12]

The SE effort in this project will cover Concept Development and Engineering Development stages. The DNV FF2 can be seeing as a prototype and due to this characteristic and the fact that the team changes every year the life cycle that is covered stop at the Engineering Development.

Usually the systems are formed by subsystems and these by components and subcomponents. The DNV FF2 follows the same approach and is formed by 12 subsystems and each of these subsystems is composed of parts or elements. Figure 3 shows the SE effort that is done in a project during the Concept development and Engineering development phases, this effort is related to the different subsystems and parts that the system is composed of.

	Phase					
	Concept development			*Engineering development*		
Level	Needs analysis	Concept exploration	Concept definition	Advanced development	Engineering design	Integration and evaluation
System	Define system capabilities and effectiveness	Identify, explore, and synthesize concepts	Define selected concept with specifications	Validate concept		Test and evaluate
Subsystem		Define requirements and ensure feasibility	Define functional and physical architecture	Validate subsystems		Integrate and test
Component			Allocate functions to components	Define specifications	Design and test	Integrate and test
Subcomponent	Visualize			Allocate functions to subcomponents	Design	
Part					Make or buy	

Figure 3 Evolution of System Materialization through the System Life Cycle.[13]

As it can be seen in Figure 3 most of the SE effort that is done during the Engineering Development phase is related to the Verification, Validation and testing activities that are also the main goal of this Thesis.

This life cycle visualization model is not the only approach; this Thesis will be based in other visualization of the engineering effort during the life cycle. The SE Vee will be used instead. Even if the SE Vee is the one that will be used, this model is also a good visual representation of the processes that are performed during the life-cycle that will help to understand the different steps of the project and what each step is composed of. The SE Vee model was used because it places a major emphasis on validation and verification activities which are the baseline for this Thesis.

2.2.1 SE Vee

The Systems Engineering Vee is a life-cycle model that gives a visual representation of the SE activities done during the project, from analyzing requirements to verification and validation of the developed product. The validation and verification processes are iterative and are performed all along the project.

The main goal of this project is to focus on the right side of the Vee, but to be able to do this; the whole Vee has to be followed.

The Vee highlights the need to define verification plans during requirements development, the need for continuous validation with the stakeholders, and the importance of continuous risk and opportunity assessment. [14]

The following will show the SE effort done during the project. This work will cover from validation and verification of the product to risk management.

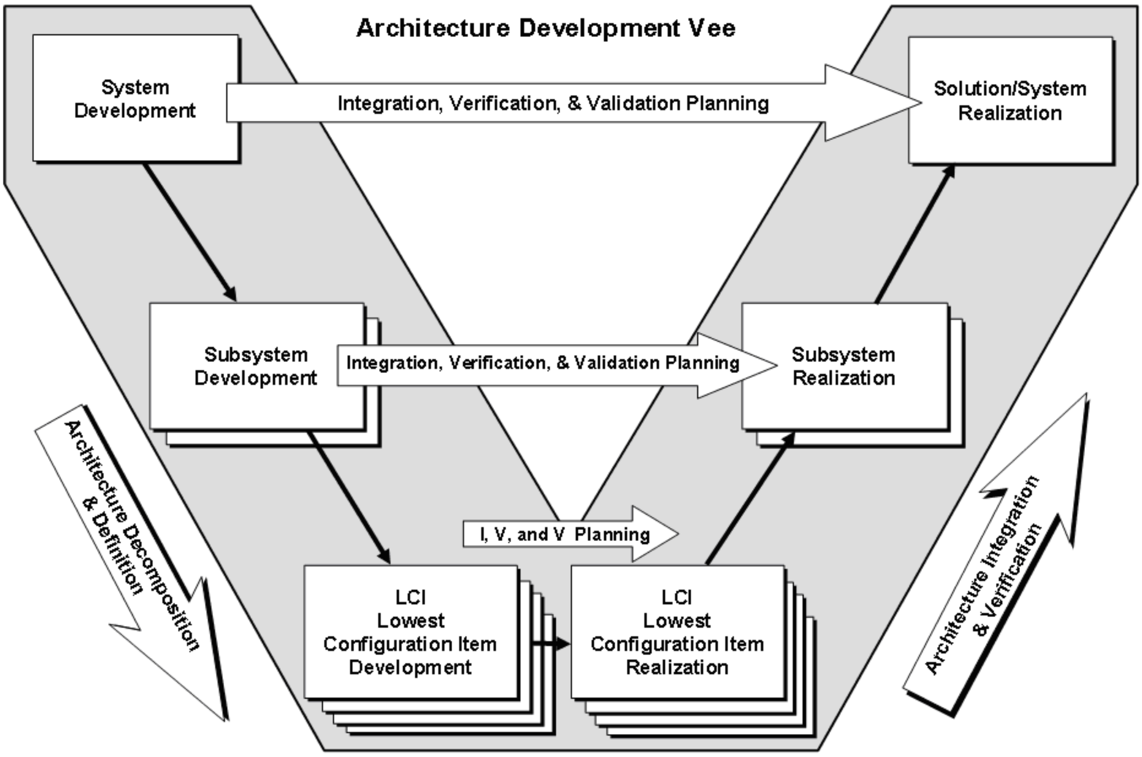


Figure 4 SE Vee model [15]

The left side of the Vee represents the concept design and development. This downward path shows the process that starts identifying and defining the requirements and goes through the definition of a high level architecture and reaches the definition of concepts and the validation of these designs with simulation activities.

The right side of the SE Vee is focused on the verification and the validation of the design and development processes that were done during the left side of it. Moving up the SE Vee is achieved by performing different VVT (Verification, validation and testing) activities. The process of going up the Vee is used to qualify the product.

Verification activities are determined by the perceived risks, safety, and criticality of the element under consideration.[16]

VVT activities are carried out throughout the life cycle. As it is reflected on the SE Vee, integration, validation and verification are activities need to be done during all the process. Verification is an iterative process throughout the life cycle and Validation is usually performed at the end of a set of life cycle task or at the end of each milestone.

The left side of the Vee covers the VVT activities during definition and design while the right side of it is where the VVT activities during implementation, integration and qualification are performed.

One of the main goals of testing is making sure that the requirements that were defined are met. Not all requirements can be measured and therefore cannot be tested, it is crucial to check the Testability and the Quality of the requirements.

Testable requirement means that each statement can then be used to prove or disprove whether the behavior of the system is correct. [17]

Requirement testability is carried out by measuring the requirements against the following characteristics:

- **Operability:** Defines the ability of a system to operate under different conditions. These conditions can be defined as normal or not so normal and can be far from the nominal. A requirement that possesses this characteristic is more testable since during the test the system can operate under different conditions.

- **Controllability:** Refers to the ability of the system to be affected or controlled by external inputs. Requirements that can be controlled by external inputs are easier to be tested in an effective way.

- **Observability:** Observability of a requirement defines how knowing the outputs, the entire system can be defined. Being able to define a system by looking at the output makes the test more efficient.
- **Decomposability:** Refers to the ability of the requirement to be related to a part or a subsystem instead of being related to the whole system. A requirement that possesses this ability can be tested in the subsystem level and therefore the results will be clearer.

- **Stability:** Stability of a system is defined when under the same inputs the sequence of the outputs remains constant. A requirement that is defined as stable is also more testable since the result will not vary when introducing the same inputs.

- **Understandability:** A requirement that has this ability provides to a person, with sufficient knowledge of the system, the knowledge that requires to understand the system.

- **Simplicity:** A requirement that is easy to understand because of its simplicity makes the testing more effective since there is not time wasted understanding it. It is important to define the requirements in such a way that they are clear at first sight.

The requirements will be testable when questioning about the characteristics defined above, the answer is positive. All the requirements that the SEM team has gather have been formulated in such a way that tries to define them as testable.

Not only is it important to measure the testability of the requirements, but the quality needs to be tested as well. A requirement is good when it possesses the following characteristics:

- **Traceable:** Every requirement must have a unique identifier. In the SEM project requirements are either from Shell, the team or the sponsors. These requirements also need to be traceable to a higher lever documents such as system requirements.

- **Understandable:** Requirements must be understandable for everyone that interacts with the system, from developers to final users. In usual projects the final users is not an engineer so the requirement has to be written in a common and understandable language. The SEM project is special in this characteristic the final user of the product are also engineers. Therefore, the requirement may have more technical language.

- **Precise:** The requirements must state the limits of its study clearly. The bounds must be clear and unambiguous.

- **Succinct:** The requirements should avoid details and unnecessary information. Only necessary information should be part of the requirement. The information that is not so relevant can be put in other document.

- **Clear:** The requirement needs to be clear and avoid different interpretations, as an example of a not clear enough requirement:

  > *Article 52 of the Shell Eco Marathon rules Chapter I: a)During weather conditions of light/drizzle, the UrbanConcept vehicles (only) may be required to drive on the track during competition with approval from the Race Director. Therefore, all UrbanConcept vehicles must be adequate for running under such conditions.*[18]

  The light rain or drizzle is not clear enough; the definition of it will change depending on the person asked.

- **Noncompounded:** A compounded requirement is constituted by sub requirements. The objective is to refine the requirement into different requirements. The fact that a requirement can be refined is important for the testing. In case the requirement is compounded by different sub requirements and the system fails to pass one of the tests for a sub requirement, the entire requirement will be defined as a failure. On the other hand, if the requirements are refined it is easier to track the problem and therefore makes the testing more efficient.

- **Correct:** A correct requirement is the one in which the needs and wishes of the final user or customer are fully covered.

- **Complete:** A requirement is defined as complete when it is able to give all the information needed to check whether the behavior is correct or not.

- **Consistent:** Requirements are consistent when they agree; this means that they do not specify different things or behavior for one same part, function or subsystem.

- **Unambiguous:** Ambiguity is closely related to semantics, since language if not well used can be imprecise and lead to misinterpretations.

- **Feasible:** A feasible requirement is that requirement that economically and physically can be tested and therefore there is a way that to test it.

Once the requirements have been defined as Testable and with Quality the testing starts.

2.2.2 Risk analysis and management

Traditionally, risk has been defined as the likelihood of an event occurring coupled with a negative consequence of the event occurring. In other words, a risk is a potential problem something to be avoided if possible, or its likelihood and/or consequences reduced if not.[19]

The risk management has usually four steps, risk identification, quantification, responses and control.

According to ISO/IEC 15288:2008:

The purpose of the Risk Management Process is to identify, analyze, treat and monitor the risks continuously.[20]

According to the DoD of the Unites States of America:

Risk management process is an organized methodology for continuously identifying and measuring the unknowns, developing options; selecting, planning, and implementing appropriate risk mitigations; and tracking the implementation to ensure successful risk reduction. [21]

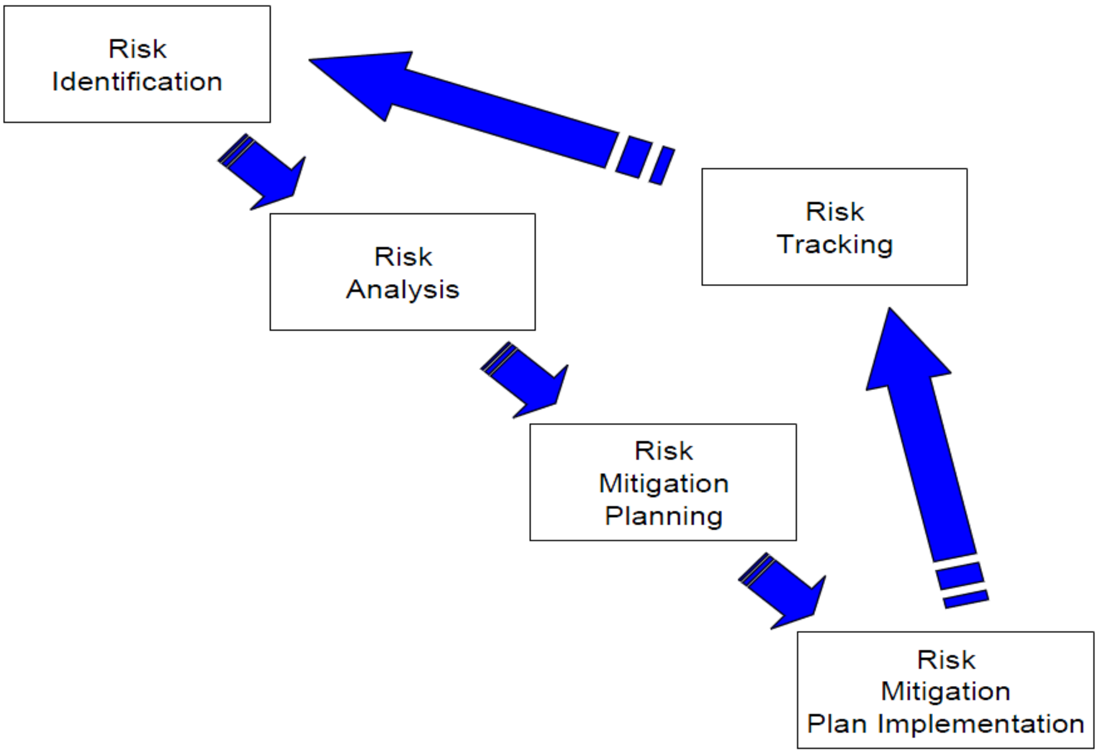


Figure 5 DoD Risk Management Process[22]

Once the risks have been identified the SE task is to define a program of analysis, development, and test to eliminate these weaknesses or to take other actions to reduce their potential danger to the program to an acceptable level.[23]

The DoD presents this Risk Management process where the first step is risk identification. The risk identification is done by interviewing the designers. Once the risks are identified is time to evaluate and weight them.

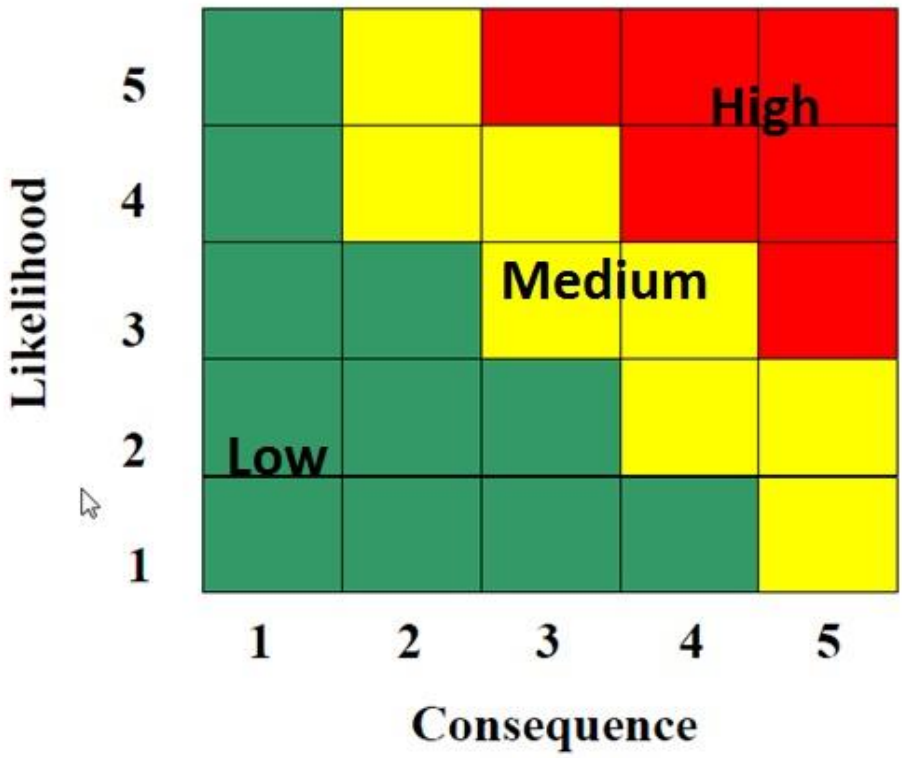


Figure 6 Risk cube display

Figure 6 displays the risks and evaluates those risks depending on their likelihood and consequences. Risks can be defined as low, medium or high risks. Risks or probability to failure can be low if they are placed inside the green area, medium if they are in the yellow and high if they are allocated in the red area.

The likelihood of a risk measures the chances of the risk becoming a reality, a value of 1 is defined as not likely and a 5 is the value given to a risk that is certain that will happen. The consequences of the risk are also measured with the same scale, from 1 to 5, being 1 a minimal or no impact consequence and a 5 a consequence that will shut the project down. In Figure 7 and Figure 8 the definition of the scale number is displayed so the reader will have a better understanding of how likelihood and consequences are defined.

Consequences

	Given the risk is realized, what would be the magnitude of the impact?		
Level	Technical	Schedule	Cost
1	Minimal or no impact	Minimal or no impact	Minimal or no impact
2	Minor performance shortfall, same approach retained	Additional activities required, able to meet key dates	Budget increase or unit production cost increase <1%
3	Moderate performance shortfall, but work-arounds available	Minor schedule slip, will miss needed dates	Budget increase or unit production cost increase <5%
4	Unacceptable, but work-arounds available	Project critical path affected	Budget increase or unit production cost increase <10%
5	Unacceptable; no alternatives exist	Cannot achieve key project milestones	Budget increase or unit production cost increase >10%

Figure 7 Evaluation of consequences[24]

Likelihood

What is the likelihood the risk will happen?		
Level		Your approach and processes …
1	Not likely	… Will effectively avoid or mitigate this risk based on standard practices
2	Low likelihood	… Have usually mitigated this type of risk with minimal oversight in similar cases
3	Likely	… May mitigate this risk, but work-arounds will be required
4	Highly likely	… Cannot mitigate this risk, but a different approach might
5	Near certainty	… Cannot mitigate this type of risk; no known processes or work-arounds are available

Figure 8 Evaluation of likelihood[25]

The ideal scenario is to go into the production phase when the risks are reduced to the minimum, as it is shown in the Figure 9. Figure 9 links the risks to the life cycle stages and also to the Relative Development Effort. The program risk decreases as the project goes on, at the beginning of the project the uncertainties are high and therefore the risks are high too. As the project evolutes the risks decrease as some of the uncertainties have already disappeared.

One of the greatest challenges to systems engineering is to steer a course that poses minimum risk while still achieving maximum results [26]

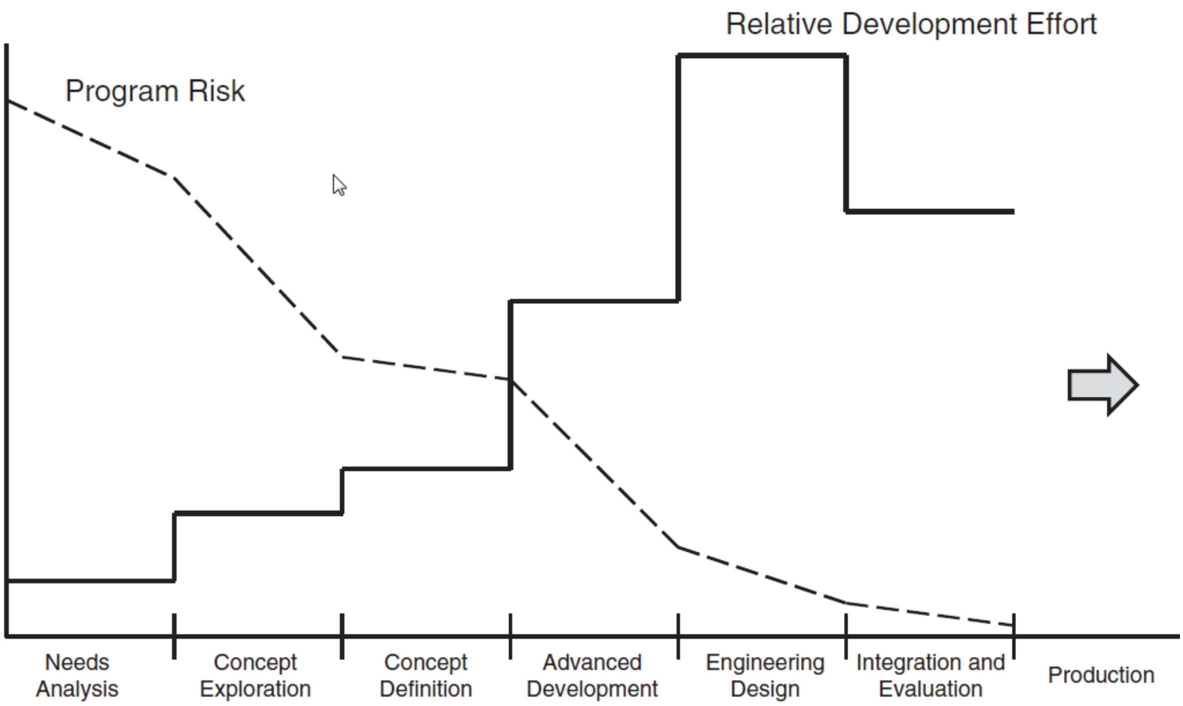


Figure 9 Variation of program risk and effort throughout system development.[27]

According to Engel every risk should be assigned to 3 categories.

1.-Transfer the risk: This option should be the chosen one when the risk can be solved or mitigated by outsourcing it.

2.-Mitigate the risk: Mitigating the risks is based on a development of a strategy that will link to each risk a mitigation activity. The mitigation plan explains how different risk and their consequences are going to be treated

3.-Ignore the risk: Some risk are irrelevant, as their likelihood or consequence is so small that are ignored. This is done so the main effort can be focus on those risks that are more likely to happen or that the consequences of happening are highly related to the final outcome of the project.

2.2.2.1 Mitigation plan.

Risk mitigation planning is the activity that identifies, evaluates, and selects options to set risk at acceptable levels given program constraints and objectives.[28]

The development of a mitigation plan is the step that follows the risk identification and that will lead the project to a decrease of risk likelihood. The strategy that has to be follow consists of identifying, evaluating and selecting possible options to deal with risks and in this way decrease the likelihood of those risks.
The mitigation plan will study the risks and define possible solutions for those risks, if possible. Sometimes the mitigation plan consists of monitoring the risk and making sure that it decreases. The actions that will be done in the mitigation plan will be linked to engineers that because of their expertise are able to handle and understand the risks.

2.2.3 VVT Methods: Testing

Testing is a subset of verification and validation, dealing with actively operating the system and verifying or validating it.[29]

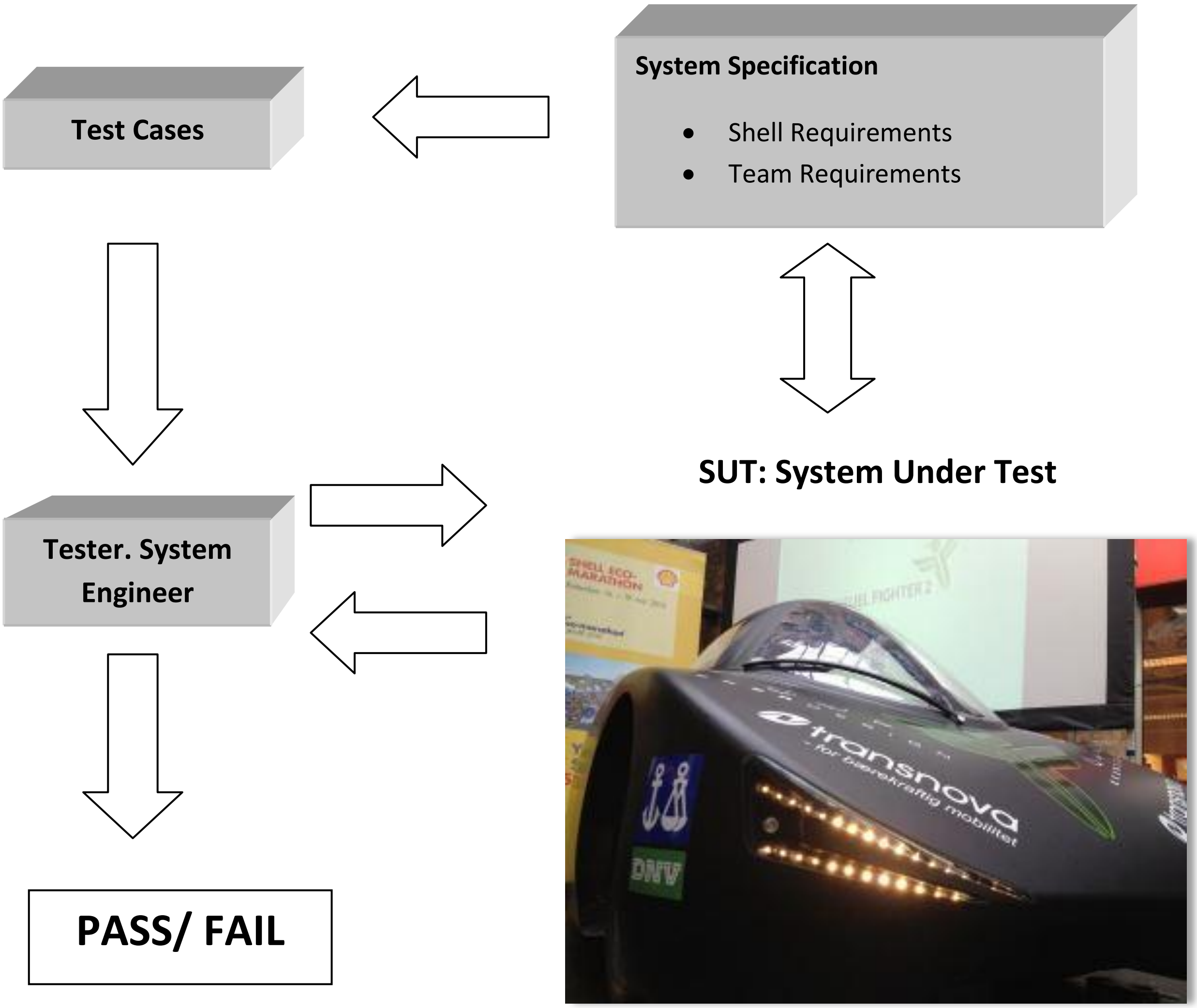


Figure 10 Fundamental System Testing Process[30]

Figure 10 shows the testing process that will be performed to the SUT, in this project the DNV FF 2. Before designing any test case the requirements have to be studied and formulated in a way that can be testable and have quality, as presented before in the Thesis. The test cases must be designed so the requirements can be checked, some of the requirements are measurable and others are not so easy to measure since they will measure performance. It is almost impossible to test completely the performance of the DNV FF 2 as its performance cannot be compared to any other known system and the team is not expert enough to be able to define a realistic and feeling-free judgment.

The System Specification is formed by “must” or “should” specifications related to the operation of different subsystems or parts of the car. Based on the System Specification, the Tester, in this project the System engineer, will define test cases, specification-directed, to validate and verify the system. When defining the test cases the system engineer must know what the system is suppose to do and also what is suppose not to do. Many times, what the system must or should do is defined and what the system is not supposed to do is not analyzed. This lack of information can lead to a system that verifies what it must or should do but the performance is not the expected one.

The test cases can be allocated in 2 different testing procedures, depending on the point of view of the engineer that designs the test process. The 2 procedures are White-Box testing and Black-Box testing.

2.2.3.1 White-box testing

White-box testing is performed at the unit level and is basically referred to testing the structure of that unit. White-box testing reflects if a part was well designed and produced, it does not check the operation or the function of that part.

The advantages that White-Box testing possesses are the deep knowledge that the VVT Engineer has of the system; this deep knowledge will allow knowing the weak points of the system and attack them during the testing to see if the system can deal with it. However, it is not always easy to find a VVT engineer with deep knowledge of the system and this can be a setback when dealing with White-Box testing.

2.2.3.2 Black-box testing

Black-box testing on the other hand is performed at the subsystem or system level and its goal is to check the operational and functional behavior of the subsystem. Black-box texting is referred to the functional test. The aim of this test is to check if a given system meets its specifications and reaches the expected outputs.

The VVT Engineers don’t need to have a specific and deep knowledge of the system, combined with the fact that Black-Box testing can be performed during all the levels of the development are advantages of the Black-Box testing. Black-Box testing is perfect to discover malfunctions of the systems.

The main difference between White-Box testing and Black-Box testing lays on the fact that the Black-Box testing is just interested in checking if the obtained output was the expected one while white-box testing worries about how the output was obtained.

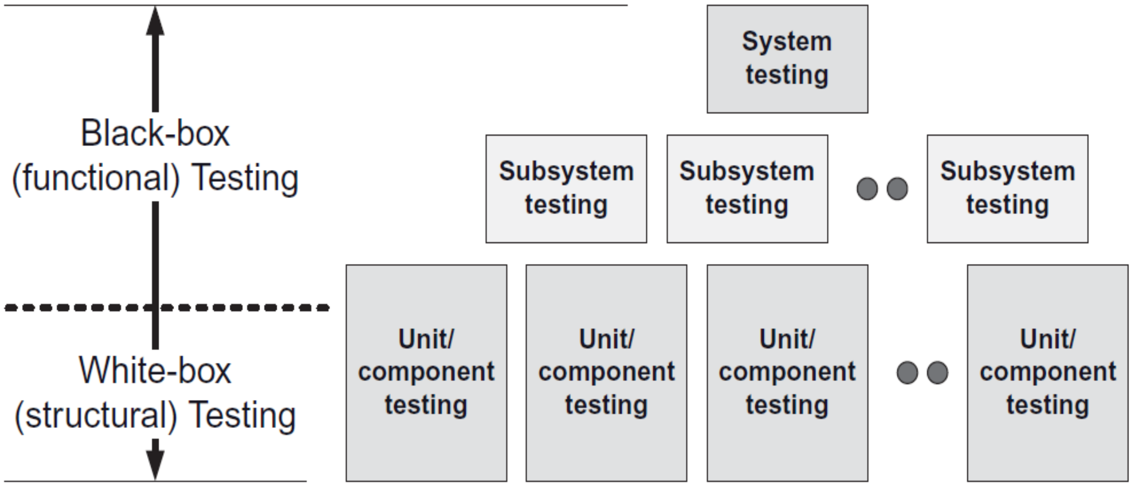


Figure 11 Hierarchical testing: white or black - box testing.[31]

The Figure 11 shows, the difference between Black-box and White-box testing. The test-target is also different, White-box testing focuses on the unit level, where the structure of the component can be tested the Black-box testing centers its attention in subsystem and system level where a functional analysis can be made.

DNV FF 2 will use both of the approaches for the test. However, the main focus will be on the Black-box testing because the SEM team will not have enough time to go into structural test of every part that was produced and besides some of the parts were bought. Thus, the main focus of the team will be to test the functional behavior of the subsystems and of the entire system.

2.2.4 VVT activities during definition

During the system definition phase the SE work consist of the creation of system requirements as well as an operational system that will define the purpose of the system. The scope of the definition phase is to create a system that fulfils the requirements and meets intended use that was designed for. The VVT activities during this phase are focused on enduring that the defined requirements are being fulfilled.

The SE needs to tailor the VVT activities, this means that, she/he should define the time in the life cycle were this test phase is going to happen. The VVT activities during definition should start early in the life cycle, when the system is being defined.

Before accomplishing the VVT activities the method of verifying the requirements, when in the life cycle and how will be verified needs to defined. The definition of how the requirements will be tested and when in the lifecycle those test are going to take place will be defined with a Requirement Verification Matrix (RVM)

			Verification method						Verification Stage				
Requirement	**Subsystem**	**Interface**	**None**	**Analysis**	**Inspection**	**Demonstration**	**Test**	**Certification**	**Definition**	**Design**	**Implementation**	**Integration (Assembly)**	**Qualification**
25 a) ii)Urban Concept vehicles must have exactly 4 wheels, which under normal running conditions must be all in continuous contact with the road. A fifth wheel for any purpose is forbidden	S.1 Body	S.5 Front suspension S.6 Rear Suspension			X				X	X			
25 b)Aerodynamic appendages, which adjust or prone to changing shape due to wind whist the vehicle is in motion, are forbidden	S.1 Body				X	X				X			X
52 e) The vehicle must be adequately ventilated to prevent driver's compartment from fogging.	S.1 Body S.2 interior	S.3 Driver					X					X	X
52 i)The effectiveness of the vehicle to run in wet conditions will be evaluated during the initial inspection phase.	Whole car						X						X
50 a)Two front headlights.	S.1 Body				X				X				

Figure 12 Example of Requirement Verification Matrix[32]

As it is displayed in Figure 12, each requirement can be verified by different means. Some of the requirements don't have the need to be verified. However, others have to be verifies and the way of doing that may differ.

- **Analysis:** Mathematical methods, simulation, charts etc. are used to analyze the requirements.
- **Inspection:** Verification of the requirements by visual inspection, some requirements can be checked just by a visual check.
- **Demonstration:** Perform some exercises under some specific conditions to check that the operation meets the specifications.
- **Testing:** Verification of a requirement by performing test cases and by gathering the data.
- **Certification:** The producer of the part that wants to be verified provides a signed certification of compliance of the specifications by that part.

The SE defined for every Shell requirement a verification method and the verification stage where the test will take part. It was also defined which subsystem was involved in that requirement and if it was any interface involved. The fact of linking subsystems and interfaces to each requirement and to the method and stage was done to know when it was going to be possible to test those requirements. This means that if the subsystem is not finished the test cannot be executed and the same with the interfaces, if one subsystem is lagging behind and this subsystem interacts with other the whole testing process will be delayed.

2.2.5 VVT activities during design

The design phase is where the development of technical solutions takes place. It is also where the SE effort focuses on defining the system architecture. In order to get a successful design and helped by the architecture, the requirements are linked to different elements.

The design can be validated by a virtual prototype. This prototype is made by software were the design can be tested. Using the virtual prototype instead of the final product, to test different scenarios, will reduce risks and some physical tests to the final product. Besides, in case of improvements of the design, these improvements can be tested first on the prototype hence reducing possible damages to the final product.

The VVT activities in this phase will qualify the subsystem and the interfaces. The design will be tested under different inputs. Solving problems at this stage will decrease the amount of money and time spent. VVT activities during design are found on the low left side of the SE Vee and it is used to verify that the design meets the requirements and to know its weaknesses and strengths. This validation activity is performed before anything is produced; it is the last step before the design goes into production.

In the ideal design scenario the design has to take into account all the stages of the product from definition to disposal. In “many-of-a-kind” industries, car industry for instance, is crucial to take all the stages of the life cycle into account. However, for “few-of-a-kind” products, designers usually don’t pay attention to the late stages of the life cycle. The DNV Fuel Fighter 2 is a “One-of-a-kind” product and its design will cover the System Development segment. The car could be seen as a prototype that is still in the development stage. One of the most defining characteristics of the SEM project is that the team changes every year. This means, that the ownership of the project changes every year, and the team that takes over will be able to lead the project in the direction that they want. Thereby, the goal of the SEM 2012 is to provide next year’s team a product that has been tested and is still in the development stage and hope that next year’s team will continue the same path.

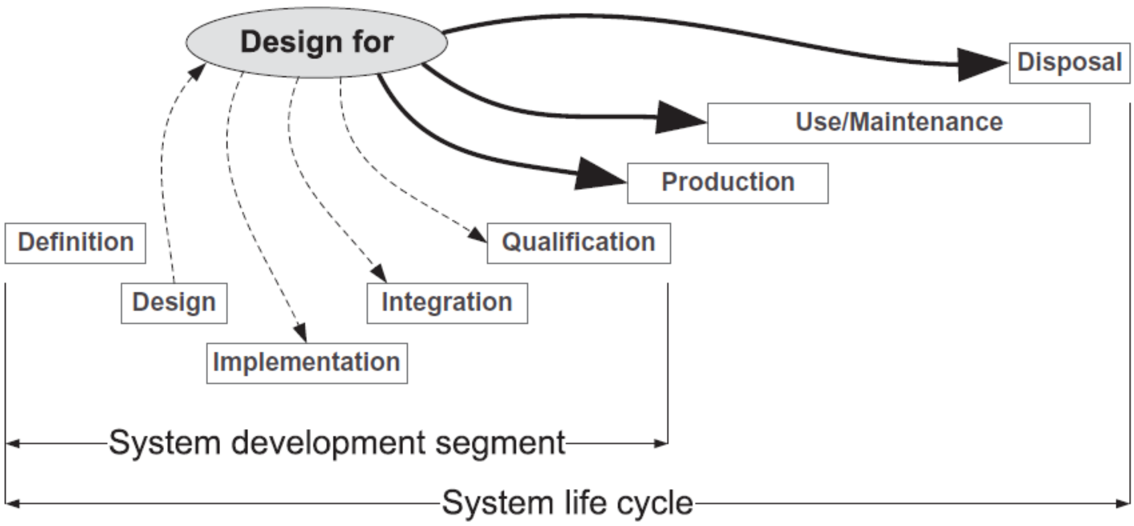


Figure 13 System Life cycle [33]

2.2.6 VVT activities during implementation

ISO/IEC 15288:2008:

This process transforms specified behavior, interfaces and implementation constraints into fabrication actions that create a system element according to the practices of the selected implementation technology. [34]

Implementation in this context refers to the creation of elements for the project. These elements will be defined in this project as parts of the subsystems. The production of some parts can be outsourced. However, every part, produced or bought, has to be tested to check that it fulfills its specifications and that has the required function or operation. The design of the test cases and the performance of these test are the job that the System Engineer will do at this stage of the project.

The implementation phase happens at the subsystem level and it can be performed concurrently with the development of the parts and subsystems.

The VVT activities during the implementation are composed of testing different parts in order to verify their design and to check if the parts meet the requirements and fulfill the need that were related to them in the beginning of the project.

Component and subsystem testing, mixes Black-Box and White-Box testing. The VVT activities during implementation contain tests that will check the functionality of the component as well as the reliability, robustness and security. White-Box testing will reflect the structural aspects of the component while Black-Box testing will check the functionality.

The Test Engineer, the System engineer in this case, is the responsible of defining which parts or components will be tested and how much will be tested.

2.2.7 VVT activities during integration

ISO/IEC 15288:2008
The purpose of the Integration Process is to assemble a system that is consistent with the architectural design. [35]

Integration is the phase were different subsystems are assembled together. In this phase, interfaces are the most crucial aspects. Therefore, one of the main goals of the System Engineer is to make sure that the interfaces behave the way they were designed for. The integration process usually starts with the definition of a virtual prototype built using virtual subsystems. These virtual subsystems are replaced by real ones until the whole prototype is composed of the real subsystems. Once the prototype is composed of the real subsystems, the prototype can be tested. The use of prototypes reduces risk as it can be used as a testing facility over the life time of the product.

This phase presumes that unit level testing has been done successfully.VVT activities during integration involve testing of the interfaces in order to make sure that the subsystems work properly and that they do not disturb each other. The testing process should go progressively testing different subsystems and its interfaces until the whole system has been fully integrated. There are diverse ways of executing the integration testing; they will be explained in the following lines.

- **Top-down Integration testing:** The testing starts with the top level component, in most cases the top level component is the system itself. In the SEM project the top level component is defined as the car. The testing strategy follows a downward path from top level to part level.

- **Bottom-up Integration testing:** The Bottom-up strategy has the same principles than the Top-down, but in this case the testing starts at the lowest level. The lowest level of the SEM is formed by the different parts of each subsystem.

- **Sandwich Integration testing:** Sandwich Integration testing is a mixture of Bottom-up and Top-down integration testing. Upper part is tested as well as the lowest part until the testing reaches a point where both parts need to be integrated.

- **Big-Bang Integration testing:** Big-Bang Integration testing is based on testing and integrating all the components and subsystem at the same time.

The DNV Fuel Fighter 2's approach to integration was a Bottom-up Integration testing, where first the parts that compose the subsystems were tested, after that the subsystems and the interfaces to finally check the whole car. The assembly strategy of the DNV FF2 will be explained in the following Empirical results section of the Thesis.

2.2.8 VVT activities during qualification

Qualification of a product is defined as the process that certifies that the product has successfully passed the performance test and meets qualification criteria defined by stakeholders.

The scope of the qualification activities is to test whether the prototype works as it was intended to. The prototype will be tested as a whole. The tests are performed under real or close-to-real environment. The work of the SE during this process is to generate and perform a Qualification/Acceptance System Test. The purpose of the Qualification System Test is to evaluate the system under the developer's point of view. On the other hand, the Acceptance System Test is from the customer's or user's point of view. For the DNV Fuel Fighter 2 the difference between qualification and acceptance is hard to find as the team effort will finish at the race in Rotterdam and down there the SEM team will be the user.

Qualification testing needs to be performed whenever the parts, subsystems and integration test have been passed successfully.

Usually it is impossible to test all the SUT's capabilities and aspects that are presented due to the interaction with its environment. Unfortunately, it is impossible to test all the functions of the system no matter how thorough the test is. Lack of resources, money, time, knowledge or just the fact that the interaction with the environment remains unknown for some cases gives the explanation to why not all functions can be tested.

The SE has to follow some rules in order to qualify the product:

- **Independence in System Acceptance Testing***:* The Team member that was responsible for developing a subsystem should not be the responsible for the acceptance of that subsystem. That is the ideal scenario, within a project with big human resources and expertise. However, The DNV Fuel Fighter 2 used the developers of the subsystems along with other team members to accept the subsystem. This was an expertise problem since the person with deepest knowledge of the subsystem was the developer itself. The SE work was to realize that the subsystem developer needed to be part of the acceptance and also to have always another team member to check the results of the acceptance.

- **Testing on Target System:** Testing should focus on the SUT in this case each subsystem or if looking to the biggest picture the entire DNV Fuel Fighter 2.

- **Preparing for System Acceptance Testing:** The responsible for the development of the subsystem will take part in preparing the data and procedures needed to perform the tests. The DNV Fuel Fighter 2 Test responsible decided that the first approach to testing should be in smooth ground to test the car at the early stages of the project and then some more realistic places where the asphalt was similar to the conditions that will be found in Rotterdam. For the first tests, The SE and the Project Manager got Dragvoll's sports centre. The following tests were performed at Dragvoll's parking lot and Trondheim Harbor was also contacted and got a positive answer from them.

- **Dry Run of System Acceptance Testing:** Dry run test are the testing procedures where the effects of a possible failure are intentionally mitigated. If the customer is going to see the test the developer has to make sure that the test performed are going to be successful. This rule is applied to The DNV Fuel Fighter 2 when investors or media are present as the team is itself the final user.

- **Performing System Acceptance Testing:** The system acceptance testing should be based on the test cases and procedures that were defined during the SysTD. The system developer has to participate in the definition of these test cases.

- **Revision and Retesting:** The subsystem developer will make revision to the system after the testing and change any document if it is necessary.

- **Analyzing and Recording System Acceptance Test Results:** The developer will take part in the review in order to analyze the result of the tests. All that information will be gathered in the SysTR.

3. Empirical Results

Once the Theory and Methods upon which the work has been based have been presented, the empirical work that was done in the project will be exposed. The empirical part of this Thesis is focused on the validation and verification of The DNV Fuel Fighter 2 and all the work that has been done to achieve that.

3.1 DNV Fuel Fighter 2: Life cycle

3.1.1 Introduction:

DNV Fuel Fighter 2 will be the car that next NTNU's SEM team will use for the following years. The ideal scenario, the one closest to the Theory and Methods of SE, is that the life cycle of the project covers all the stages from Definition to Disposal. Probably if the project was defined to last for more than one year this could be done. However, each year the whole team changes and the time constrain does not allow the team to design the car so it can cover the whole life cycle. The SEM 2012 sees the following teams as users of a prototype that has been designed and built this year. The VVT activities that are covered in this Thesis are linked to definition, design, implementation, integration and qualification stages. Acceptance of the product is done by the user and therefore it should be done by the following SEM Teams. However, defining the final user for a project such as the DNV Fuel Fighter 2 is not an easy task, but it will try to be explained in the Discussion part of the Thesis.

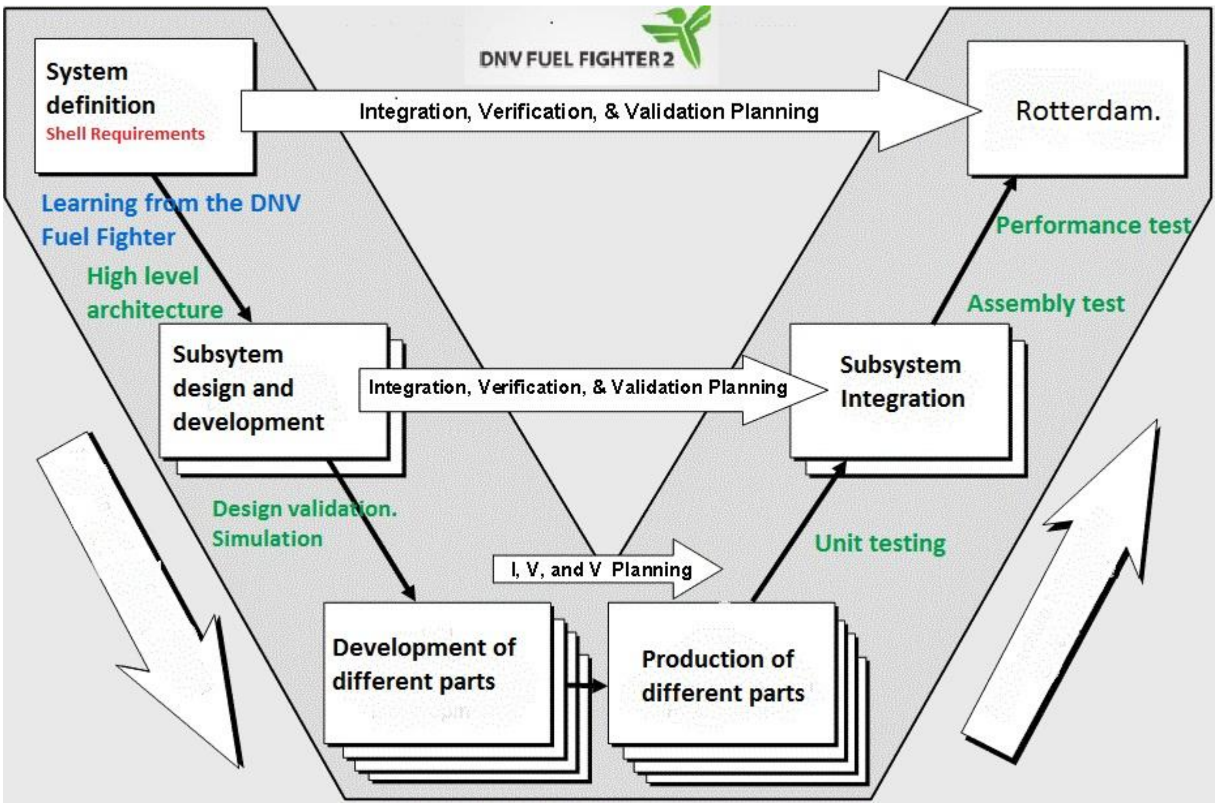


Figure 14 Vee model for the DNV Fuel Fighter 2[36]

The SE Vee will be used as a visual representation of the work that has been done. Figure 14 shows how the SE Vee has been tailored to fit in the DNV FF 2's needs. As mentioned before the SE effort will reach the qualification stage. The SE work for the DNV FF2 started in the fall semester of the year.

During the first semester, the left side of the Vee was covered so the work done during the spring semester was the continuation of that work, from the lowest part of the Vee to the upper-right side of it. The SE work that was done during the first semester of the SEM project consist of defining a new System Architecture, based on the one used in the SEM 2011, developing a Trade-off analysis to study all the decisions that were made, a requirement checklist in order to make sure that the solutions that were designed met the specifications and a detailed attention to interfaces.

The requirements were coming most of them from Shell, a thorough analysis and allocation of these requirements was done also during the first semester. The requirements were also refined and their testability and quality was checked. It was especially important to have the old system architecture to be able to relate the requirements to the subsystems that formed the project.

The new system architecture is based, as said before, on the architecture developed by A.Welland [37] for the DNV Fuel Fighter. The architecture from the previous year was used in order to identify early in the project, a rough estimation of cost and schedule and most important to set responsible team members for each subsystem. Interfaces, as well as the subsystems, had responsible team members that were the ones having contact to each other to reduce the risk of failure.

As it is represented in the Figure 14, there are testing procedures all along the SE Vee. The testing activities during the left side are focused on the validation and of the design with simulation while the VVT activities of the right side are performed when the part/subsystem is produced and its function needs to be checked. The right side of the Vee covers the VVT activities during definition and design, thus the main effort of this Thesis will be in the VVT activities done during the implementation, integration and qualification.

The DNV Fuel Fighter 2 team, made the decision of developing a new car based on the new scenario that Shell defined for this year's competition. The new scenario is basically that for the first time in the Shell Eco-Marathon Europe race the competition will be held in a street-track in Rotterdam. The new track made a new suspension necessary and there was not space in the old body to implement it, therefore the development of a new body was necessary. Once in Rotterdam, it was discovered that many of the other competitors had stiff suspension as the DNV Fuel Fighter 1. However, having suspension gave the car the ability to be the fastest car in the second half of the track where the turns were closer to each other this also allowed the car to coast for a longer distance. Besides, the car was also able to enter the turns faster than it was planned when the track analysis was made. In the track analysis the speed that was defined for the turns was between 20-25 km/h but the car was able to enter the turns up to 33 km/h. This speed increase gave the team freedom to design a better race strategy.

Another major change from the previous year was to change the propulsion system, this year for the first time in NTNU's history the SEM team entered the battery electric class. The decision of changing form fuel-cell to BE was based on the knowledge transfer from previous year, telling the SEM 2012 team that the hydrogen is less reliable and that in case of lack of knowledge about hydrogen BE was a better and safer decision. The SEM 2012 lacked of expertise about hydrogen and therefore the decision of entering the BE class was decided. The previous NTNU SEM teams had had really good results in the Fuel-cell category and entering a new category was a great challenge for the team. It was discovered that the competition of BE cars is much tougher than the FC class.

3.1.2 Visualizing the life cycle:

SE needs to have a clear vision of the project status and the life cycle stage where the project is at any time. It is important that the system engineer knows how to provide that information to the rest of the team. Therefore the SE team made the decision of implementing a visual board where the milestones of the project could be easily accessible for the team members and would be a tool for SE and Project Manager in order to track the status of the project.

As it was explained in the Theory and Methods part, the life cycle is a framework to which the decision gates and milestones are linked. The SE team of The DNV Fuel Fighter 2 implemented a visual board where the work breakdown structure (WBS) of the subsystems' could be seen; this board also defined the milestones. Some of which were also defined as Decision gates. The board was used to keep track of all subsystems and to address the risk related to the fact that some of the subsystems slipped. This board was used as a tool to be more efficient and therefore to keep a good number of days in order to test the vehicle, under different circumstances.

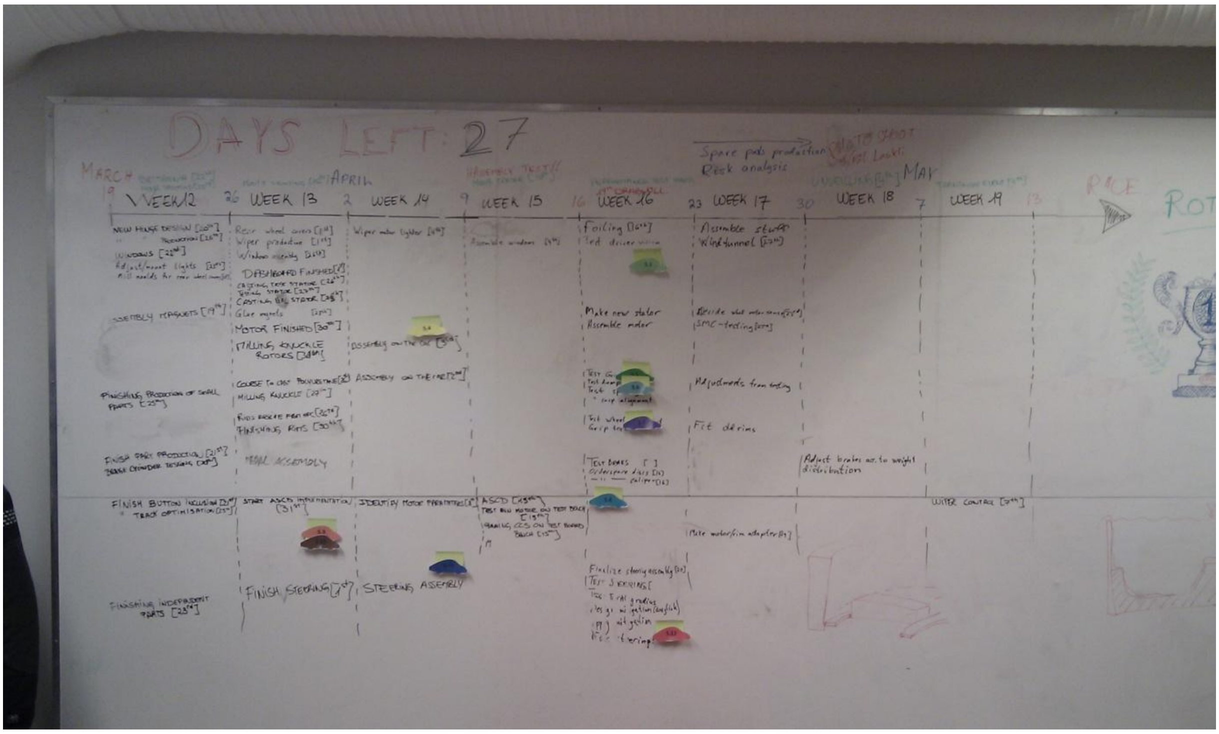


Figure 15 WBS that could be found at SEM's office

The board where the WBS could be found was at the SEM office and it was facing the work places of most of the team members, for those that were facing the other side of the office it was also really easy to visualize. The SE team saw a need of communication within the team and especially among subsystem responsible. The WBS board was used as a complement to the Stand-up meeting that were held and that can be found in Tonning's "Implementing Lean Systems Engineering in the DNV Fuel Fighter 2 project"[38].

The WBS board was separated in the remaining weeks till the race that were left when it was implemented. Each subsystem was reflected with a car and a number. The fact of putting the number of the subsystem instead of the name of the responsible was done to avoid people from outside knowing who was the team member lagging behind. This could affect the person's feelings and that could lead to a demoralization of the team member. To get the information of what was going to be done each week in each subsystem the SE team had interview with all the team members. SE work is not only found on the technical part and that is why in the WBS apart from technical milestones the media events that the team had to attend were also displayed. The days that were left till the race was also in the WBS board, so the team members could organize themselves in the most efficient way.

For the SEM team most of the milestones were postponed. However, almost all the decision gates were reached, even if it was late. One of the most challenging moments was to define what to do with the new engine. The milestones for the engine were delayed, and the project reached a point where the decision of competing with that engine had to be made. When that decision gate arrived, all the possibilities were studied but due to some production problems of the new engine, that made it less efficient, the decision gate was defined as Unacceptable. Luckily for the SEM team the engine of the DNV FF was available and this was why the project was not defined as unsalvageable.

The decision of going with the old engine was made by the cybernetic engineer as he was the person whose work was delayed by the engine. The parameters of the engine needed to be defined in order to optimize the control system. This is not one-day work and therefore setting a deadline was completely necessary. The idea of setting a deadline was a decision made by the Cybernetic engineer with the Project manager and agreed by the system engineer. This deadline was also postponed two days since the team thought that the new engine could be used and the characteristics of this engine were better than the ones from the old engine. Unfortunately, it was seen that this was not the case as some production errors were found. Looking back to that moment, the SE has thought many times that if a stronger deadline had been defined the time to develop the control system would have been longer, but on the other hand if the new engine would have performed as expected the decision of delaying the deadline would have been a winning decision.

3.1.3 Life cycle processes

The Theory and Methods section introduced the different processes that are involved in the life cycle. The processes that were done by the SE in this project are related to Project Processes and Technical Processes. Most of the processes that the SE has done are technical. Stakeholder Requirement definition, Requirement analysis, Architectural design, Implementation, Integration, Verification and Validation are the processes that have been executed by the system engineer. Among the Project Processes the only one that was done by the SE team was the Risk Management.

The fall project covered the stakeholder requirement definition, requirement analysis and the architectural design. The spring semester and consequently this Thesis covers implementation, integration, verification, validation and risk management.

3.1.4 Role of SE inside the DNV FF2

In the Theory and Methods part the twelve system engineering roles were presented. Most of the roles are composed by many different tasks and the SE of the DNV FF2 can't be completely related to all the activities that a role is composed of. However, if the idea is to define the roles of the SE of the DNV Fuel Fighter 2 it has to be pointed out that most of the roles are covered, some of them completely and some of others just partially. The following lines will explain what was done by the SE team that can be associated to the roles already presented in the Theory and Methods part.

- **Requirement owner role:**
  The SE team can be identified with this role since a big effort in allocating, managing and maintaining the requirements was done. The System Engineers were the owners of the requirements that after were allocated to different team members according to their subsystems. The SE effort was also on developing a functional architecture. This role was covered by both of the systems engineers involved in the project.
  In the Appendix I: Requirement Allocation how the SE divided and linked the Shell requirements to different subsystems and responsible team members can be seen.

- **System Designer role:**
  The system engineers that embraces this role is the responsible of designing a high level architecture and that is exactly what the SE did during the fall semester of the project. This task and the ones that are found on the Requirement owner role overlap and that is why the SE of the DNV FF2 can be found in both roles.

- **System Analyst role:**
  The SE team can be allocated here since a performance model was used to track the status of the project. However, not all the roles covered by the System Analyst Role have been performed by the SE. For instance, the SE team have not been in charge of handling the budget, that task has been executed by the Project Manager.

- **Validation and Verification role:**
  As stated previously in the Thesis the main SE effort that the writer has done for the project is related to Validation, Verification and Testing activities. The System Engineer has acted as a Test engineer defining and performing test cases and test procedures. The effort has been focused on verifying that the design met the requirements that had been defined in the early stages of the life cycle. The writer would have appreciated a test team since the beginning of the project to go more into detail of testing. Unfortunately, the SEM team is a student project with a limited amount of time and resources and it has been impossible to have a test team and the SE has performed also the V&V role.

- **Glue role:**
  The glue role is a really wide range role and it could have many interpretations. It can be seen as the role of the person that is the responsible of integrating the system. This was covered by the SE as the interfaces were one of the most crucial aspects that the SE was concerned about. However, the writer understands this role as the role that looks for weaknesses in the organization and tries to solve them. The SE team of the SEM has performed this role in such a way. When weaknesses were discovered the SE team decided to act, for example the team was late on production and one of the things that were triggering this problem was discovered by the SE team. One of the roots of the problem was that each team member was responsible of producing all its parts and had not the help from any other team member; in addition there was no knowledge of what the other team members were producing. The SE team decided to paste on the workshop wall the architectural design where all the subsystems were divided into parts. Then a color code was defined. The green color means that the part has been produced, the red that the part or subsystem is critical, the orange means that the apart or subsystem is under production and finally the yellow means that the part is waiting for something or someone to be produced. Figure 16 shows visually all the color code.

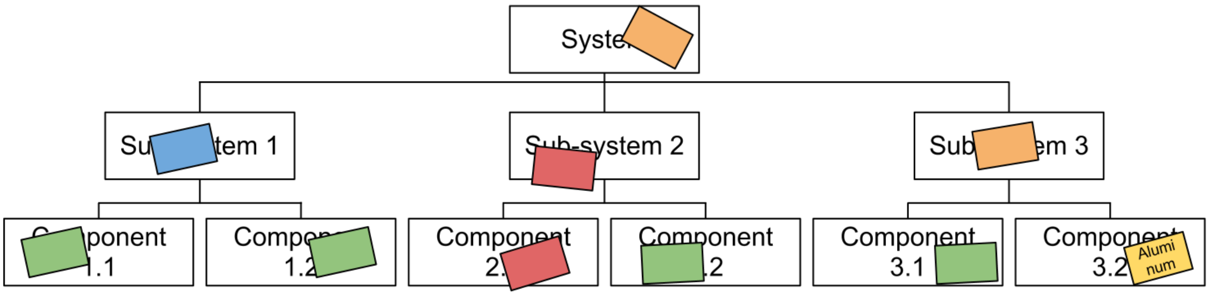


Figure 16 Visual representation of the color code.[39]

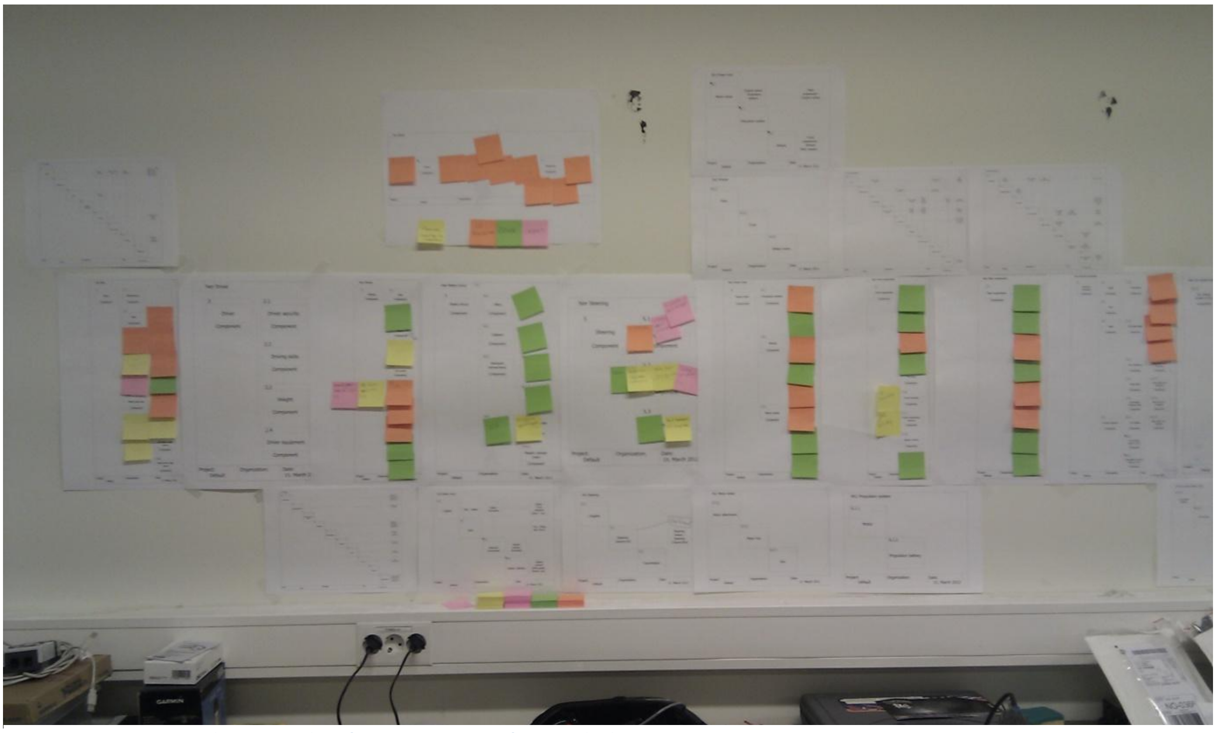


Figure 17 Board that can be found at SEM's workshop

Figure 17 is the real representation of Figure 16, it was located in the workshop next to the car and where most of the team members spent most of their time. To find more detail about the wall and how it was used Tonning's "Implementing Lean System Engineering in the DNV Fuel Fighter 2 project" should be read.

The Glue Role that the SE team acquired was also the triggering role for embracing other roles. This means, that when the SE team discovered a lack of something or a weakness the role changed so the issue could be solved.

- **Technical Manager role:**
  The tasks that are involved in this role were shared with the Project Manager. The PM was the responsible of the budget related tasks and he also asked team members to elaborate and share a weekly report in order to track the project status. The task of tracking the project status was a shared, the PM received the weekly summaries and the SE team updated the WBS board. Oluf Tonning as the other system engineer of the project introduced the Stand-up meeting to keep also track of the project status and to help communication within the team. More insight into stand-up meetings in Tonning's "Implementing Lean System Engineering in the DNV Fuel Fighter 2 project".
  The Technical Manager Role also deals with risk management and the SE that are involved in this role are the owner of the risk management plan. The SE effort that was done in the risk management is found on 3.1.5 Risk analysis and management.

- **Coordinator role:**
  This role was performed by the SE when problems arose. An example, during the race in Rotterdam, in the first attempt the team lacked of organization and to solve that a meeting was organized. In that meeting, called Stand-up meeting by Tonning, how the team was going to be organized for the following attempts was discussed. The result of this meeting was that the team members knew their tasks and there were no more organizational problems during the race.

As mentioned, most of the roles have been covered this year. This is a good way to show the wide range of effort that both systems engineers have done for the project.

3.1.5 Risk analysis and management

The SE team of the DNV Fuel Fighter 2 made a huge effort in defining, analyzing and making a mitigation plan for the risks of the project. The risk management of the project is linked to the VVT activities as the good planning of those activities can lead to a decrease of risk. As mentioned in the Theory and Methods the first step in the Risk Management is to identify the risks.

The first approach to identify the risks was a risk session, where the risks of different subsystems were defined. The subsystems were refined into their different parts and the goal was to link risks with parts in order to track the risks and possible mitigation activities. The outcome of this session was that the SE team had risks related to each part of the car. The SE team used Google docs to store, share and update the information about the risks with the team members. An example of one of the Google doc sheets that was used can be found in Appendix III: Risk Management.

The next step was to interview each team member to have a deeper view of each risk and how could these risks be mitigated. The team members were asked to define the likelihood and the consequences of the risks in order to measure it, values from 1 to 5 were given to the likelihood and to the consequences. In order to make the risk evaluation easier for team members the SE introduced the “bet system”. This system was based on asking the team members about their confidence in their subsystems. They had to say how much money they would bet that their subsystem would perform successfully. This was a first approach to risk analysis. The betting system did not work as expected, as it was based on personal feelings and confidence and not based on facts.

In the Theory and Methods, it was presented that the risk when entering production should be almost none. However, due to the characteristics of the SEM project, where the team members are students, risks were not reduced before going to production. In fact, many risks were discovered in the production phase.

Risks in the project were divided into resource and technical. The VVT activities are closely related to both technical risk of the project and resource risk. Technical risk could be seen during the testing; the more testing the more the technical risk will decrease since the car and each different subsystem would have proved that they work as designed. The problem of this project was that due to some resource risk becoming reality the time for testing was reduced.

The risks were updated each week, until the SE team realized that the risks were constantly increasing and that this could lead to a drop in team's morale. However, even if the risk update was stopped the SE designed a mitigation plan to cope with all those possible risks.

The mitigation plan deals with the problems trying to avoid them or at least to reduce its consequences. The first step before developing the mitigation plan it was to allocate risk in the 3 options that were explained in the Theory and Methods and that are a reflection of A. Engel's work.

Risks had to be transferred, mitigated or ignored. The DNV FF2's approach has been either to mitigate or to ignore the risks. The ignored risks were the ones that had a small likelihood and small consequence.

There were different risk mitigation activities. Most of the risks were mitigated by producing spare parts or by following them up. An example of the mitigation plan can be found in Appendix IV: Mitigation Plan.

The fact that the SEM project is a student project where no one is an expert caused more problems than just the fact that many risks were identified during production as it has been mentioned before.

Probably the biggest problem that the SE had faced when identifying and defining risks is the lack of experience of the team members. This lack could lead the risk analysis to the feeling side or to the fact that Engineers can be certain of something just because they do not have enough experience and expertise to know more about it.

3.2 Validation, Verification and Testing activities of the DNV FF 2.

The validation and verification process used in the project is a reflection of the Theory and Methods explained in the beginning of the Thesis. As it is shown in the Theory and Methods part, the VVT activities need to be performed throughout the entire project.

The testing phases related to VVT activities during definition and design were done in the first semester of the project. The quality of simulation software's gives the opportunity to validate the design before it is produced.

During the second semester, when this Master Thesis took place, the focus on VVT activities was on the implementation, integration and qualification activities. The DNV Fuel Fighter 2 defined four different test phases, unit testing, assembly, performance and race test, which are related to the right side of the SE Vee.

The test time that was expected at the beginning of the project was way bigger than what it finally turned to be. The DNV Fuel Fighter 2 spent testing the last 4 weeks before going to Rotterdam. Unfortunately, that does not mean that tests were performed every day. As it has been said before, the project was late on schedule and this made the test time to be considerably reduced. The team was behind schedule due to several factors, such as late delivery of materials, the fact that for a fair amount of time the team could not work after closing hours of the workshop and that the use of the workshop is not exclusive for the team. Besides, once the mechanical subsystems were tested the team had to wait for the assembly of the engine and the control system since they were not ready to be implemented in the car.

In each test procedure some rules were followed. These rules stated that before performing any kind of test some things needed to be defined. What was going to be tested the testing procedure that was going to be used, the expected output, the requirements for passing the test, the material needed and the personnel were the things that needed to be defined. All this information was gather in SysTD (System Test Description) and SysTR (System Test Report). The SysTDs and SysTRs were defined for each test phase and can be found on the Appendixes of the Thesis

The test procedure was not finished until a review of it was done. This review was an informal gathering with the different team members to discuss the testing. This review was based on the Acceptance test Review that Engel presents on his book. The review of how the test went was done by asking the team members and by hearing their conversations. After each test, what should be change or adjust was asked to the team members. Example of an Acceptance Test Review in Appendix VII.

3.2.1 Unit Testing:

Unit testing is related to the VVT activities during implementation that was defined in the Theory and Methods part of the Thesis. This testing is held at the subsystem level and consists of testing different parts of the subsystems. Subsystems must be checked before being assembled into the car. The responsible of each subsystem is also the responsible of the unit testing of the parts forming that subsystem.

The Unit testing is the testing phase where the simulations made on the computer are validated. During the simulation, the parts were checked with the software and it was time to check that the design was right. It is also the phase where problems with the production are observed and tried to be fixed. In case these problems cannot be solved by small manufacturing adjustments, the part or the subsystem needs to go back to concept phase. The Unit Testing phase is where White-Box testing is performed and structural characteristics of different parts are studied. Due to time and resource constrains it was not possible for the DNV FF 2 to perform structural analysis of all the parts that a subsystem is composed of.

The engine is one of the subsystems that the project is based on; it has interfaces with the rear suspension, the control system and the engine wheel. The suspension and the rims were designed to fit in the new engine that it was being built. The problems appeared when the team discovered, by testing the engine at SmartMotors, that the new engine was not efficient enough. It is believed by the team members that the inefficiency of the new engine was caused by production problems. This fact leaded the team to the decision of competing with the motor that was used in 2011. As it was mentioned before, the engine has interfaces with several other subsystems and the fact that the new engine was not going to be used caused some troubles. One of the main problems was that the new engine was designed to be about 10 kilos lighter that the old one. Luckily, the changes that needed to be done were minor adjustments but the use of the old engine, on a car that was designed for the new engine, could jeopardize the car and specially the result on the race. The engine test is based on its functionality and therefore it is defined as Black-Box testing.

Batteries are part of the propulsion system and testing them, if theory is followed, would be Unit Testing. The problem and why the writer has defined the Battery test as Assembly test is because it requires interactions with other subsystems. Tests performed to the drive train are allocated in the Assembly test part of the Thesis and they will be explained there. However, some of the tests depending on the point of view of the Test Engineer could be defined as Unit testing, depending on where the attention is focused. The Test Engineer of the DNV FF2 believes that for better understanding of the test procedures it is better to explain all the test that were done to the drive train all together.

3.2.2 Assembly Test:

The assembly test refers to the VVT activities during integration. The DNV Fuel Fighter 2 is divided into 12 subsystems that must be integrated successfully. The main focus of integration is on the interfaces. The theory and methods section of this Thesis presents the ideal scenario and activities in order to test the car. The theory refers to having a prototype in order to test the car and reduce risk by doing so. According to A. Engel's "Verification, Validation and Testing of Engineered systems" the car in the SEM project is seen as the prototype. However, for the DNV Fuel Fighter 2, the car is seen as the final product and due to time constrains it has been decided not to use a test frame in order to reduce risk while testing.

The assembly test phase was divided into 2, the mechanical assembly test and the engine and the control system. The main goal of this phase was to test all those Shell Requirements that are not related to performance and to check the interfaces. Making sure that the car fulfils Shell requirements is of capital importance because if the team fails to do so disqualification will be the result. How the technical inspection is done by Shell Marshalls during the competition is presented in the Master Thesis "Utvikling og bygging av bil for deltakelse I Eco-Marathon konkurransen" by SEM 2012 team.

For the mechanical subsystems, the integration testing is done in the Bottom-up order. The Bottom-up integration testing starts at the part level, then goes to subsystem level and finally to system level.

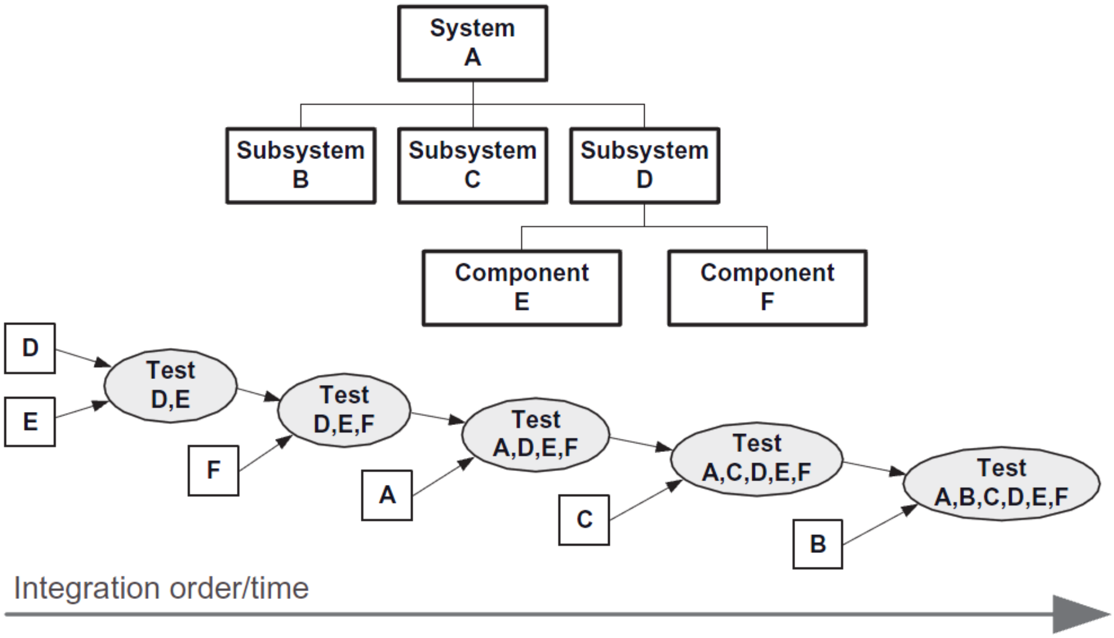


Figure 18 Bottom-up integration

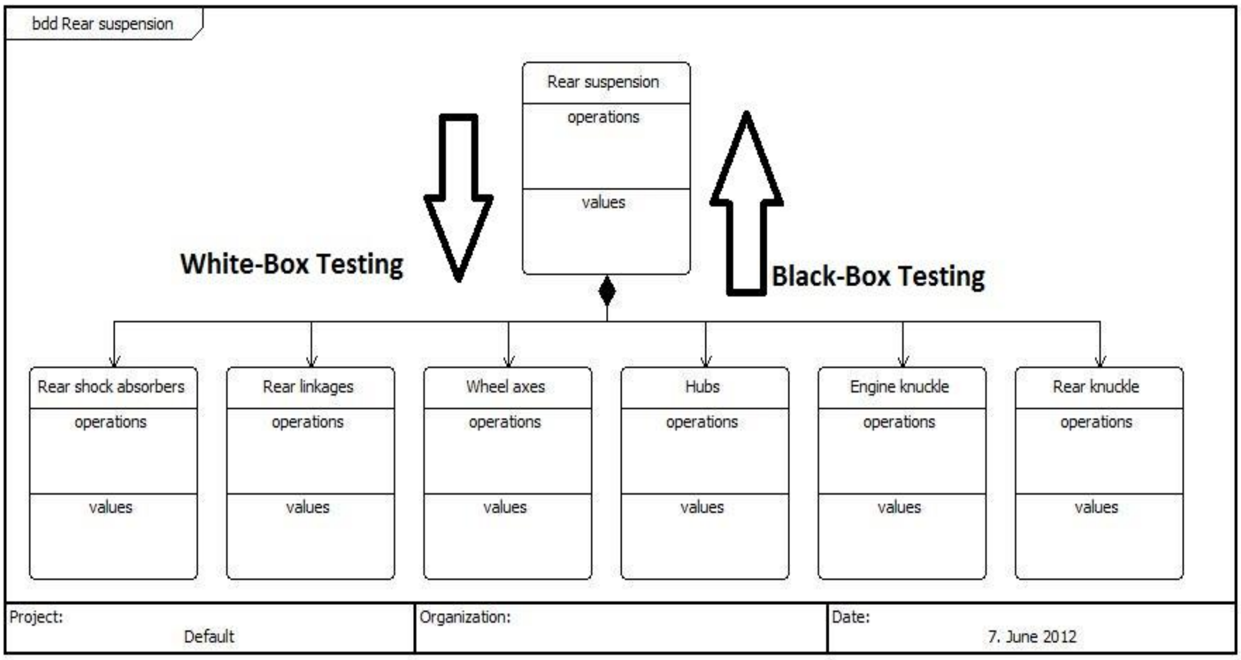


Figure 19 Rear Suspension subsystem

Figure 19 shows the different parts that compose S.6 Rear suspension. The parts are tested by visual inspection or they come certified by the producers. The tests performed to the component level are White-Box Testing and their goal is to test the structural behavior of the parts. Once parts are verified, they are assembled. The tests that are done to the subsystem to check its functionality are named Black-Box Testing. This procedure is done with the rest of the mechanical subsystems. When all the parts from the mechanical subsystems are verified the subsystems are assembled together and the result of that assembly is tested.

For the Control system and the Propulsion system, the approach is different since they are not divided into parts as the mechanical subsystems. In this case, the assembly part consist of assembling both subsystem and testing the assembly.

3.2.2.1 Mechanical Assembly Testing

The idea of using a test frame to integrate all the mechanical subsystems instead of using the new monocoque was considered. Integrating different subsystems into the monocoque without testing them increases the risk of damaging the monocoque. The optimal option would have been to build a test frame and test all the different mechanical parts on it. This solution would have decreased the technical risk related to different parts' safety.

The monocoque was new and it had not been tested under race conditions so its performance remained unknown. The fact that the body´s performance was unknown elevated the risks of failure.

The team chose not to build a test bench due to time and resource constrains. Building the test bench would have delayed the entire project. This lack of time could have been avoided if the test frame was already designed and manufactured during the fall semester. Therefore, The DNV Fuel Fighter 2 encourages the next year´s team to consider making a test bench concurrently to designing new parts in order to test all the mechanical parts all together.

The first testing day was done indoors in a smooth surface. The NTNUI let the team use Dragvoll's sport center. It was an excellent place to test the visibility of the car, to check Shell requirements and also to test the mechanical subsystems. The team thought that it would be a good idea to test the car for the first time on a smooth surface where the car was not going to be extremely demanded. The way that the assembly test phase was designed is that the tests have to go from less to more challenging to the different subsystems.

The tests were defined before going to Dragvoll as well as the tem member that will be there, the material that will be used and the expected output of the tests.

During the first day of testing some cones were set in zigzag. At the beginning the cones were quite far from each other, the steering was performing well, then the distance between the cones was narrowed and at the 3rd trial, when the cones were quite close to each other, one of the pulley mounting points that are used to support the Kevlar cable of the steering went off. The surface where the pulley's mounting point was glued to the carbon fiber was not big enough. This problem was fixed by increasing the contact area of that piece with the monocoque so the friction will be higher.

Figure 20 SEM team measuring the distance to perform the visibility check

After the first test, when the car was in the workshop one of the rims experienced a small crack, the team thinks it was due to some problem during manufacturing at HPC. The fact that one of the rims failed was a major shock for the team members as the same could happen to the other rims. In order to solve this major risk the team decided to have the 2011 team's rims as spare for the competition. Last year's rims needed some adjustment so they can fit the actual suspension.

Once the mechanical parts and their interfaces where tested and checked that they worked, the car was taken to Dragvoll's parking lot to test it under real asphalt and friction. The car, still without the engine on it, was pushed by the team members while the driver was seated and reached a speed of almost 25 km/h. The mechanical parts behave really well, no other rim was damaged and the last year's rim showed a reliable behavior. The good behavior of the 2011 team's rim made the team consider racing with the old rims as each rim is approximately 200 grams lighter than the new ones.

Figure 21 Detail of how the speed was measured.

Figure 22 Test day at Dragvoll's parking lot.

3.2.2.2 Propulsion and Control system assembly

The other assembly test part refers to the engine plus the control system. The assembly test of these two subsystems was held at SmartMotors. In order to test the propulsion with the control system the DNV FF2 used a test bench that is located at SmartMotors. Not having an in house test bench made not possible to test as much as the team wanted as the sponsor was not always available.

The complete drive train was tested on test bench with different loadings at different speeds to measure efficiency for different operating points. The test bench was also used to study battery behavior for low battery voltage and over current. The DNV FF2 had 2 different types of batteries, one was provided by Altitec and the 2 others by Gylling.

The second battery pack from Gylling was ordered since the team thought that the one that was already delivered was not going to be able to provide enough energy to finis one attempt. This decision was made based on the tests made at SmartMotors. The issue with this decision is that it was based on the tests made to Altitec's battery, it was seen afterwards that it was not necessary to had ordered another battery from Gylling since the first one was able to supply more than enough energy. The cybernetic and electric engineers of the DNV FF 2 had almost no time to test and that is the reason why the test were made for just one of the batteries, the one that was supposed to be the race battery.

The outcome of these tests was used to discover that under voltage protection was needed to prevent complete stop while racing, torque limitation to prevent under voltage and over current to prevent still stand while racing. Measurements were used to find most energy efficient velocity/torque profile for the given track.

Figure 23 Gylling's battery packs

Figure 24 Altitec's battery pack

3.2.3 Performance Test:

In the Theory and Method VVT activities during qualification was explained. In the DNV Fuel Fighter 2 the VVT activities during qualification was divided into 2 consecutive tests. Performance test is the first stage of this testing procedure.

Performance test consist of testing the whole car under realistic environment and to check how the car behaves under those circumstances. Once the car has passed this test it must be ready to run under any circumstance that may occur during the race in Rotterdam.

Previously in the Thesis it was presented how the assembly test will be performed in 2 different and concurrent ways. One way was with all the mechanical subsystems together and the other one the engine along with the control system.

The DNV Fuel Fighter 2 faced a schedule and time problem to perform this test stage. Reducing time to test, as it has been proved in different years of the SEM project, is a huge setback. The idea, after interviewing the team members, was to start the performance of this phase on April 19th but as it has been exposed in this Thesis, the late delivery of the engine delayed the performance of this test phase to May 1st. The tests were performed in Dragvoll's parking lot, as it was impossible to get the airport or the army installations that last year's team used, the team also got the approval to test in Trondheim Havn but due to weather conditions and time problems it was not possible to test the car there.

The Driver and the cybernetic engineer were the ones performing the tests, as the mechanical parts had already been tested in previous tests. However, the tests were also planned to check if the rear suspension could handle the old engine, since as it has been stated before is about 10 kilos heavier that the new engine that was designed. The main tests were in order to tune the starting parameters to the driver's weight. The starting parameters were tested with different starting slopes to check if the engine was able to supply enough torque. The results of this test was to see that the engine had problems to apply enough torque when it was uphill, the cybernetic engineer changed some parameters and vectors to solve this issue but it was decided that the parameters were going to be optimized in Rotterdam once the starting slope was known.

Other tests that were performed were maximum speed, which due to testing space it was not achieved; the place was not long enough. The ability of the car to enter the turns at high speeds was also checked; the team got a really nice surprise as the car was able to corner faster than was it was thought. When cornering at high speeds it was also discovered that if the car was coasting the turning was smoother, this is because the engine was not supplying any torque to the car.

As a man-handling system, the driver training was also really important since the race-track this year. Since it was not possible to simulate the race track the test was focused on getting to know the car and losing any kind of fear the driver may have. The test was performed under a light rain, so the car was also tested under rainy conditions.

The outcome of the test was really positive; the morale of the team concerning the race was really high at this point and the driver felt really confident with the car. The writer of this Thesis was also the driver and that is why it can be said that the confidence level on the car increased exponentially after this test. The DNV Fuel Fighter 2 encourages future team to give the driver time to know the car, know the sounds and learn not to worry about them and also to get familiar with the steering.

Figure 25 Performance test at Dragvoll's parking lot.

3.2.4 Rotterdam

Rotterdam was where the competition was held and as mentioned before it was a street track for the first time in Shell-Eco Marathon Europe. The team sees the Race as another step for the qualification of the car. Last year's SEM team understood the Race as the acceptance test phase but for us the definition of final user is different and therefore the Race test is another step of the qualification and not the Acceptance test. This distinction has also things to do with the fact that last year's car was the evolution of an already existing car and the qualification of that system was already been done. However, this year's car is completely new and needed to be qualified

The part of the Thesis will explain the technical inspection and the tests done during the test days and competition days.

3.2.4.1 Technical Inspection:

The Shell technical inspection is seen by the SE as one validation step. It is not seen as the acceptance because Shell is not defined as final user of the vehicle. The objective of this inspection is to make sure that cars fulfill the requirements and it is compulsory to pass it in order to be able to compete.
In the inspection all Shell rules are checked by different marshals. The Shell marshals use tablets, as it can be seen in Figure 26, where the just make a tic when a requirement is checked. They are able to do that because the requirements have been refined until they are just a pass/no pass requirement. The SEM team also worked in that way with the requirements. First, a requirement allocation was done and then in order to verify that the car fulfilled those requirements, the SE refined them.
The team had no problems in passing the inspection, and this allowed the team to enter the track to test the car during the test days and competition days. To get more information about the technical inspection the reader should go to the Thesis "Utvikling og Bygging av bil for deltakelse i Eco-Marathon-Konkurransen". In order to have a view of how the technical inspection is done the Thesis presents two pictures, Figure 26 shows the Marshals with the tablet and the bar-code reader to identify the car and Figure 27 shows how the dimension test is performed.

Figure 26 Shell Marshals checking the fire extinguisher

Figure 27 Checking the dimensions

3.4.2.2 Race Test:

The Race test is defined as the last phase of the VVT activities during qualification. Race test is a complement to performance test. The performance test is focused on testing the car under different environment and circumstances while the race test was intended to simulate the race conditions in Rotterdam.

Performance test will qualify the car to run under different settings and the race test will optimize the car settings to be as good as possible in Rotterdam. This part will give the reader a view of what happened in Rotterdam during the test day as well as what happened in the race attempts. The writer will explain completely all the issues that happened and how the team solved them as the race in Rotterdam is the test where the vehicle will be qualified as a prototype. Issues involved in the race have to be mentioned so future System Engineer will know the input and outputs of every test.

This test phase is also intended to be training for the drivers so they can improve their driving skills. The fact that this year's competition will be on a street track and the track is more complex than previous years makes the driving skills an important issue that should be trained thoroughly. Unfortunately, as mentioned before in the Thesis, the SEM test procedure faced a time and testing place issue and it was not possible to simulate the track in Trondheim. Besides, Shell did not supply any team with information about the different elevations that could be found along the track; hence it was impossible to recreate the track in Trondheim

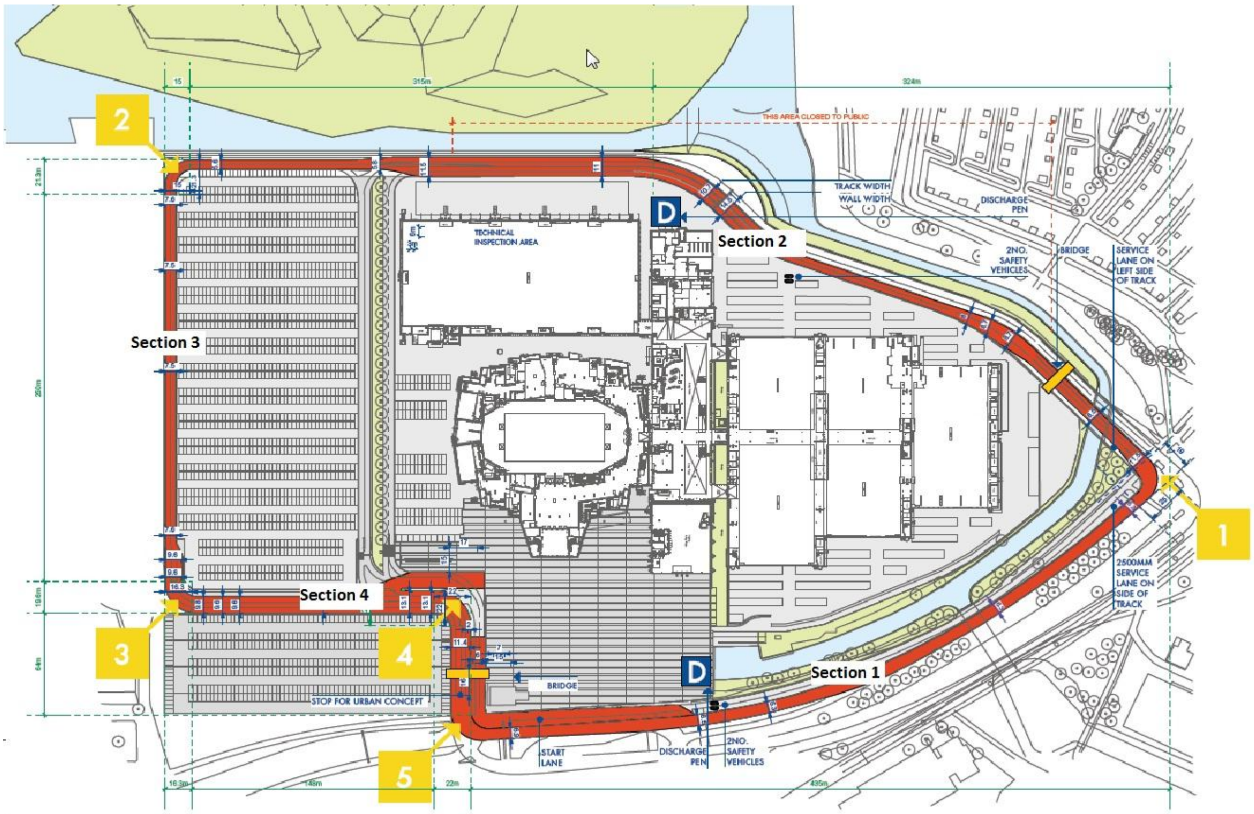


Figure 28 Race Track Ahoy Rotterdam

Figure 28 shows the race track in Ahoy Rotterdam, as it can be seen there are five 90 degree turns. The car needs to stop completely each lap between the fourth and fifth turn and then restart again. The SEM team divided the tract in four sections; the first one was from the start line until the first turn, in that first turn section 2 started and went until 2 turn was reached, there section 3 was introduced that lasted until turn number 3 and from that point till the stopping place was section 4. During the competition days there were testing times for different categories, for Urban Concept cars, DNV Fuel Fighter's category, 3 time spots

3.4.2.3 Problem and solutions:

First testing day:

Problems:

- When the car reached a considerable speed the window from the door opened and the driver had to finish the lap driving with one hand and holding the window with the other one.
- In section 2, the car did not react to the driver's requirements and was not able to accelerate. The same thing happened twice at the same exact place and one other time in the middle of section 1.

Study of what causes those problems:

- When the engine was asked to provide higher torque the battery had to supply the engine with higher current. When the current that the engine was asking to the battery was too high the BMS shutted the battery down and there was no option to restart it again, therefore the attempt was over. There was also a problem with the coasting code, when this option was enabled the car set the reference speed to zero and the control system was not able to know the spinning speed of the engine. Then, when another section button was pressed and the reference speed was set to another value, which was not zero, the energy that the battery had to supply was too high and the BMS shutted down.

How were problems solved?

- The door was taped as a temporary fix to be able to run more time and get to know the track.
- The team decided to have two ways to solve the problem in order to reduce the risk of not being able to compete. Both batteries were going to be tested to see which one will provide the best chance of having successful attempts. The code of the propulsion system was change to reduce the maximum torque that the engine could supply and also the coasting will no longer set reference speed to zero; hence when pressing coasting button a deceleration function was triggered and the car was consuming a small amount of energy. To trigger "real" coasting, no energy consumption function, and the driver needed to step on the brake pedal. These changes were made for the Gylling battery. The other approach was to tune the starting parameters for Altitec's battery.

Second day testing:

The testing plan wanted to test both batteries and the new code for Gylling's battery. The plan was to start the testing with Gylling's battery and to check if the problem with the BMS shutting down the battery was solved. The team had to be quick in order to change the batteries and flash the new code on the car in the same pit line.

- The car run for 3 laps with Gylling's battery and the result of the testing was successful.
- Testing Altitec's battery the driver noticed that this battery was not able to supply the same energy than the other one, the acceleration was slower and the top speed was not reached at any time, while with Gylling's battery top speed was reached every lap. After the first stop, the car was not able to start again; the battery could not supply enough energy to start the car.
- The next step was to simulate a valid attempt.

Issues discovered after the testing:

The team discovered the outstanding mechanical capabilities of the car. During the attempt the driver noticed some rubbing coming from the right side of the car. One of the pieces from the Front Suspension was bent. This piece was replaced by other one with some small modifications

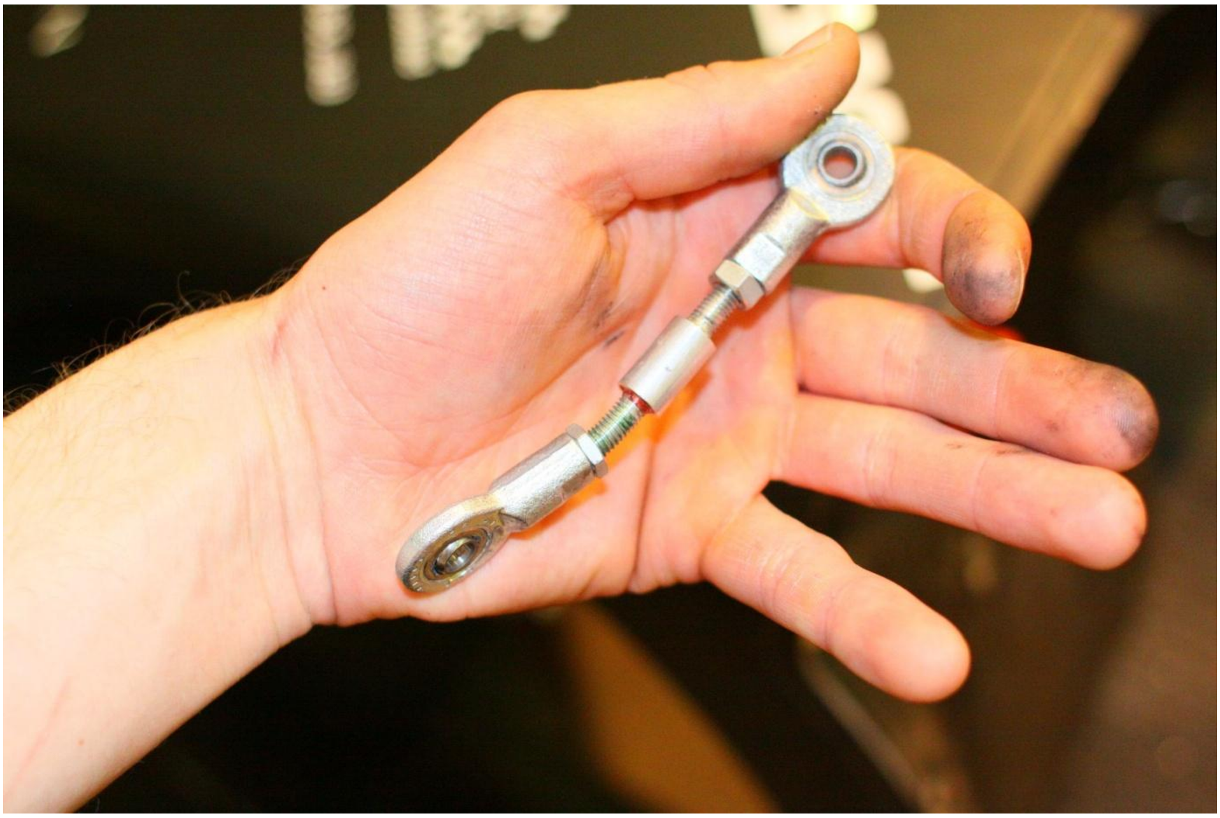


Figure 29 Piece from the Front Suspension that bent.

<u>Competition:</u>

- The first attempt failed because the door opened again in the same place and at the same moment.
- The second attempt was the first successful one. Result of 136km/KWh.
- Miscount of the number of laps of the attempt. An extra lap was done making the attempt in 11 laps and not in 10 as it is stated in the rules
- Due to weather conditions there was fog in the car but the visibility was still correct

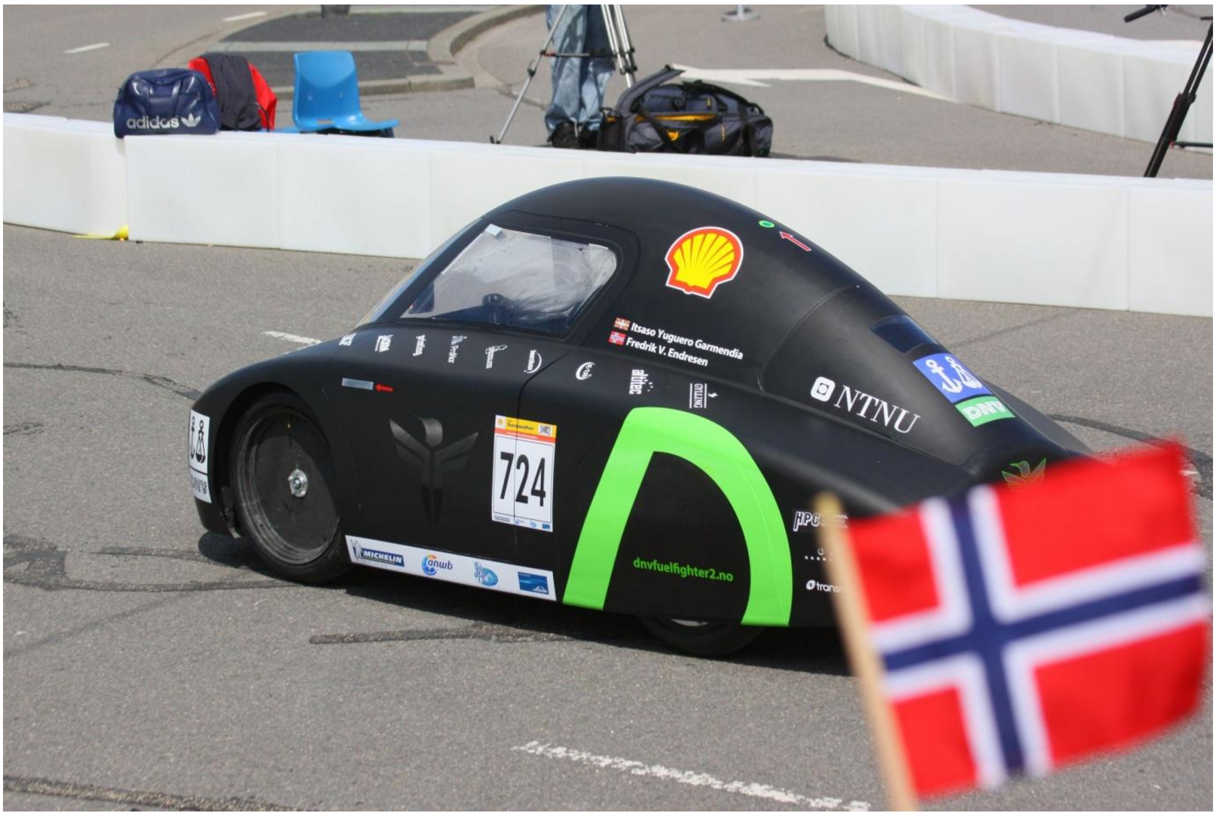


Figure 30 Finishing the first valid attempt

Issues discovered after the testing:

The time of the 10 laps was 37:50 minutes still far from the 39 minutes that was the maximum time that it could be used in one attempt. It is really important to be able to enter the finish line as close as possible to 39 minutes. The car had shown to be reliable, something that for instance DNV FF was not, but the result was still far from being what the team expected.

In order to improve the result, the air gap was reduced and the fly start routine was tune for the new engine conditions .Even the rims were changed, the team put the old rims into the car as they are lighter than the new ones. The driving style was also going to be changed.

Outcome of the changes:

The 10 laps were in 38:36 minutes, it is a notorious difference with the previous time. Unfortunately, the result was not as good as expected the result was 163 km/KWh. The team still does not know which the root of the improvement was since many things were different from the prior attempt.

The fourth attempt was going to be used to try any idea that could lead to an improvement in the result. This attempt finished abruptly, the Kevlar rope of the steering broke and the car crashed. The driver had already noticed that something was going wrong with the steering, 2 laps before the crash, the steering capabilities to take turns to the right started to decrease and every time the steering was harder.

Figure 31 Front-left part of the car after the accident

4. Discussion

The main topic of the Thesis is Validation, Verification and Testing of the DNV Fuel Fighter 2, therefore the main thing will be to discuss whether the intended scope has been reached or not. The Verification, and Validation activities that have been done have helped the team to pass the technical inspection without problems while previous years it had become an issue, even if all the previous team had also passed the inspection. It needs to be pointed out that the DNV Fuel Fighter 2 has been the first NTNU SEM car able to have a valid attempt already in the first competition day. The vehicle was a reliable car that was not able to make all the attempts valid due to small issues that the team should have been more concern about. However, even if the DNVFF2 has been a reliable car some things could have been improved if more time would have been invested in testing. The drive train needed to be tested in deeper detail but due to time constrains it has not been possible. The biggest problem that had to face the system engineer was the lack of time and resources to be able to perform better VVT activities. The time and resource problem has been an inherent problem in the SEM projects.

The writer wants also to discuss the definition of final user of the DNV Fuel Fighter 2. Depending on the definition of the final user the qualification activities may change. Qualification activities are performed from the organization’s point of view and Acceptance tests from the customer’s or final user’s point of view. Therefore, setting a common definition of the final user inside the team is important, also to understand the point of view of the final users. The writer defines as final user the sponsors and next year’s team. At the beginning of the semester the driver was also seen as final user but after going into more detail the system engineer, that is also the driver, understood that the driver in this SEM year was the person responsible of conducting the last test phases, where functionality of the entire car is tested. The sponsors are seen as final users and the team has to meet the specifications that they set. The sponsors of the DNV FF2 are looking for media attention that the project can give to them, what the team offers to them is PR. Thus, the team has made huge effort in order to fulfill the stakeholder’s need for attention. The view of the PR has been as an extra work that had to be done by the team members. The Systems Engineers with their global vision of the project understand that PR is value adding and that it will enable future teams to find founds.

Future SEM teams are also seen as final users as they are going to be the ones “inheriting “the DNV Fuel Fighter 2. The DNV Fuel Fighter 2 performed qualification tests but is final user’s duty to accept the product and as next year’s teams are defined as final users they will be the responsible of conducting those tests.

Another discussion that the writer will like to introduce is the definition of systems engineering. Is SE a discipline or an attitude? The writer has no background on systems engineering and she was first introduced to System Engineering in the fall semester. It has been hard for Systems engineers to answer that question and the writer knows about the difficulty of giving an answer as well. However, from her small experience she will try to give her modest point of view about the discussion. It is obvious that SE involves practices that could lead to the definition of SE as discipline. However, the attitude towards life and problems are vital for a system engineer. The writer reflects for herself “Before this project I had no clue about systems engineering and despite that I have been able to be the system engineer in a rather complex project, so is it because of my attitude?” The discussion could be infinite but the writer thinks that at least from her experience systems engineering is an attitude. This attitude is based on how the engineers identify the problems and try to solve them. Many engineers are just focused on making their subsystem as close to perfection as possible without understanding that the product functionality is based on all subsystems and that the aim is to get the best operational characteristics of the whole. In addition, some engineers are always trying to solve problems in the most complex way, the System Engineers or at least the writer of this Thesis is closer to Occam's razor way of thinking applied to science that states that "When you have two competing theories that make exactly the same prediction, the simpler one is the better one."

Writer's background is mechanical and therefore she had also the same vision that some team members. The understanding of what engineering means is related to the design and manufacturing of a part or something tangible, something physical and that is why for some team members was hard to value SE work at first. However, the writer does not want to place all the blame of this underestimation in the team members' background. The way of improving things is always to track the things that could be improved and probably the way that SE work has been introduced to team members should be different, more involvement and education of the team members is needed. The System Engineers of the SEM have discovered that the way of getting information and involvement from the other team members is to directly talk to them and show interest about the thing that they are doing. In addition, to be even more successful it is really important to be flexible. The SE team has been flexible in order to adapt their work to team's needs. The way to be so flexible it has been to tailor already known System Engineering practice to the project, making the necessary changes.

As mentioned before, the writer has felt that sometimes the effort that she was doing was not seen as value adding. In comparison with the previous year where the SE work was seeing as vital. The writer thinks that in student projects like the SEM when people really appreciate SE work is when problems arise. It is important to know than in a project like the SEM there are always times where the stress is high and the workload too, the SE duty is to try to make the effort as efficient as possible, using boards, visual signs etc.

Last year's team had a lot of troubles that made them even being close to shutting the project down. This year, when problems appeared the systems engineers have become an important part of the solution, canalizing efforts and coordinating actions.

The Value of systems engineering in this project, as explained before, has been hard to prove sometimes since the beginning for mechanical team members but the Project Manager told the writer how crucial and helpful it has been for him systems engineering. The fact that the Project Manager could see easier the value of System engineering is related to the fact that for many aspects inside the project the Project Management effort and the Systems engineering effort have interacted. SE work is not just related to technical aspects of the project, SE are the ones that have a complete view of the project and of the different efforts that are done within the team, from mechanical or technical aspects to PR and management.

For the first time in SEM project a system engineering team has been involved. Each Monday SE meeting was held. During those meetings what was going on in the SE efforts inside the team and new ideas were discussed and developed. It proved to be effective as it was used to foresee problems or to solve the ones that had already happen. Besides, the writer had a lot of help from the other system engineer as he had system engineering background.

The writer will also like to stress out the important of legacy. The DNV FF2 had inside the team a team member form previous year and it has also count with the help of the cybernetic engineer of the DNV FF. The knowledge transfer that those two engineers have given to the team was absolutely crucial and it helped the team to gain knowledge faster and thereby improve the characteristics of the old car. As stated over the Thesis the team lacked of expertise in some aspects and this lead the project to higher risks. Therefore, having two engineers involved in this years' team decreased that amount of risk related to uncertainties.

The writer suggest that the SE effort in the SEM project 2012-2013 focuses on the last stages of the life-cycle, meaning, operation, maintenance and retirement. It would be a great work to qualify the actual car as it was a final product instead of just a prototype. In order to achieve that, a complete and modular test frame can be built. The fact of making it modular makes it more challenging but also more useful as it could be used by different SEM team even if the car is changed.

5. Conclusion

This project has served the writer to gain experience in systems engineering and in group-work. Working in group is really challenging as sometimes feelings are involved. The importance of having another system engineer during the second semester was quickly seen by the writer and also by the Project Manager. It was important because the systems engineering “strength” in the team increased and was easier to get people involved.

As explained in the Discussion section the definition of final user changed along the project, the writer thinks that this happened because she gained knowledge and insight into the project and was also able to see that the project is an ongoing process. The fact of being able to see the process as not static gave the vision to the writer to change the definition of final user and to adapt the VVT activities so that change was taken into account.

The main goal of this work was via a definition and development of VVT activities to qualify the car. The outcome of the implementation of the VVT activities to the DNV Fuel Fighter 2 has been to provide a reliable car that made two valid attempts but that some of the invalid attempts were due to minor errors that competition does not forgive but that could be solved in less than a minute.

The final result of the competition was not better due to the definition of the drive train. Analyzing the VVT activities to find possible solutions is one of the main tasks of the system engineer when she adopts the test engineer role. The system engineer thinks that one of the problems related to the drive train issues is inherent to the SEM team. This problem is that just 2 team members out of 14 were related to the drive train, this difference in human power sets a big gap between the mechanical parts and the drive train. While the mechanical properties of the DNV Fuel Fighter 2 were outstanding compared to competitor the car was lagging behind in the drive train.

Therefore the main goal of next year’s team will be to define a better solution for the drive train that will lead the car to the victory. The identification of these problems has been done during the qualification of the car, thus during the VVT activities designed by the system engineer. Another thing that the next year should do is to keep on with the risk analysis done by the SEM 2012 they should use it as a starting point to their analysis.

References

1. ISO/IEC 15288:2008, Systems and software engineering – System life cycle processes, Geneva: International Organization for Standardization, issued 1 February 2008
2. ISO/IEC 15288:2008, Systems and software engineering – System life cycle processes, Geneva: International Organization for Standardization, issued 1 February 2008. p.44
3. ISO 9000:2005, Quality management systems -- Fundamentals and vocabulary, Geneva: International Organization for Standardization,2005.
4. Sheard, Sarah A., The Value of Twelve Systems Engineering roles, Proceedings of NCOSE, 1995
5. Boehm, Barry. "Integrating Software Engineering and Systems Engineering.
6. Fisher, Jack. "Systems Engineering for Commercial Space Programs," *Proceedings of NCOSE*, 1992.
7. Kosiakoff,A., Sweet,W.N, Seymour, S.J,Biemer, S.M., *Systems Engineering Principles and Practice,* 2nd Ed., John Wiley &Sons, 2011 p 70
8. ISO/IEC 15288:2008, p. 10
9. INCOSE Systems Engineering Handbook v. 3.2.1 INCOSE-TP-2003-002-03.2.1 January 2011,p 21
10. Ibid ,p 23
11. ISO/IEC 15288:2008, Systems and software engineering – System life cycle processes, Geneva: International Organization for Standardization, issued 1 February 2008
12. Kosiakoff,A., Sweet,W.N, Seymour, S.J,Biemer, S.M., *Systems Engineering Principles and Practice,* 2nd Ed., John Wiley &Sons, 2011 p75
13. Ibid p84
14. INCOSE Systems Engineering Handbook v. 3.2.1 INCOSE-TP-2003-002-03.2.1 January 2011 p27
15. Adapted from Forsberg, K., H. Mooz, H. Cotterman, *Visualizing Project Management*, 3rd Ed., J.Wiley & Sons, 2005
16. INCOSE Systems Engineering Handbook v. 3.2.1 INCOSE-TP-2003-002-03.2.1 January 2011 p.124
17. Engel.A, *Verificaton, Validation and Testing of Engineered Systems,* 1st Ed., John Wiley &Sons,2010 p 266
18. Shell Eco-Marathon Rules Chapter I, 2012
19. Conrow, E. H., *Effective Risk Management*, 2nd Ed., American Institute of Aeronautics and Astronautics, Inc., 2003, p 435
20. ISO/IEC 15288:2008, p. 29
21. Risk management guide for DoD acquisition, Sixth edition version 1.0 Department of defense USA august 2006.p.3
22. Adapted from Risk management guide for DoD acquisition, Sixth edition version 1.0 Department of defense USA august 2006 p.4
23. Kosiakoff,A., Sweet,W.N, Seymour, S.J,Biemer, S.M., *Systems Engineering Principles and Practice,* 2nd Ed., John Wiley &Sons, 2011 p 123.
24. Ibid p124
25. Ibid p124

26. Kosiakoff,A., Sweet,W.N, Seymour, S.J,Biemer, S.M., *Systems Engineering Principles and Practice,* 2nd Ed., John Wiley &Sons, 2011 p 120.
27. Ibid p 121
28. Risk management guide for DoD acquisition, Sixth edition version 1.0 Department of defense USA august 2006 p18
29. Engel.A, *Verificaton, Validation and Testing of Engineered Systems,* 1st Ed., John Wiley &Sons,2010 p.351
30. Adapted from Engel.A, *Verificaton, Validation and Testing of Engineered Systems,* 1st Ed., John Wiley &Sons,2010 p 352
31. Ibid p 353
32. Adapted to The DNV Fuel Fighter 2 from Engel.A, *Verificaton, Validation and Testing of Engineered Systems,* 1st Ed., John Wiley &Sons,2010, p.66
33. Engel.A, *Verificaton, Validation and Testing of Engineered Systems,* 1st Ed., John Wiley &Sons,2010, p. 88
34. ISO/IEC 15288:2008, p. 42
35. ISO/IEC 15288:2008, p. 44
36. Adapted to the DNV Fuel Fighter 2 from Forsberg, K., H. Mooz, H. Cotterman, *Visualizing Project Management*, 3rd Ed., J.Wiley & Sons, 2005
37. Welland.A, Master Thesis for The DNV Fuel Fighter, San Francisco, 15.07. 2011
38. Tonning,O. ""Implementing Lean System Engineering in the DNV Fuel Fighter 2 project".NTNU,Trondheim 2012
39. SEM Team 2012 "Utvikling og Bygging av bil for deltakelse i Eco-Marathon-Konkurransen". NTNU, Trondheim

Appendix I: Requirement Allocation

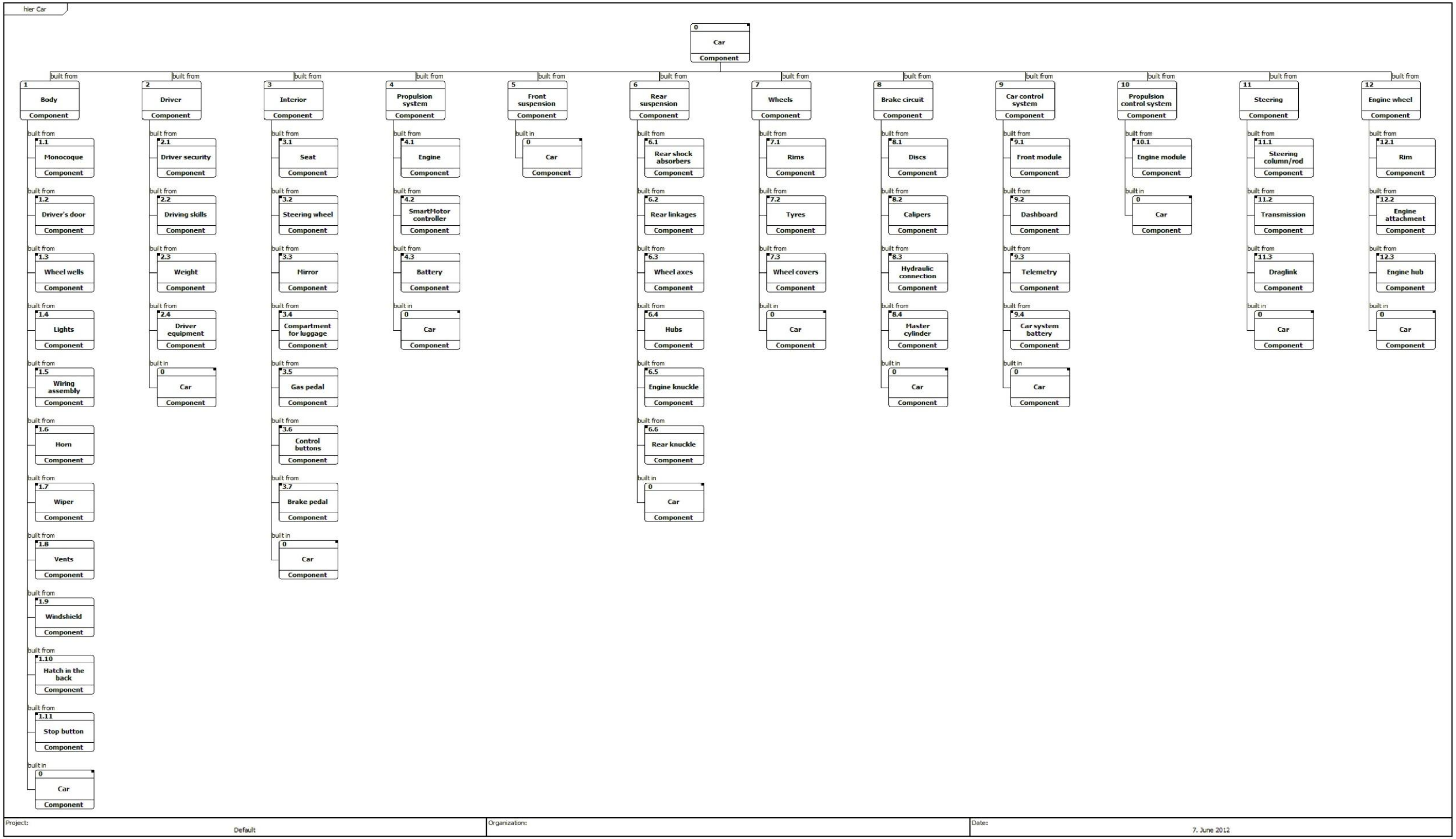
1.1.-Vehicle design:

Article	Requirements	System	Responsible	Status
25 a) ii)	Urban Concept vehicles must have exactly 4 wheels, which under normal running conditions must be all in continuous contact with the road. A fifth wheel for any purpose is forbidden	S.1Body S.5 Front suspension S.6 Rear suspension	M.H.S E.S A.Q H.G H.S	
25 b)	Aerodynamic appendages, which adjust or prone to changing shape due to wind whist the vehicle is in motion, are forbidden	S.1 Body	M.H.S P.T.L A.B.E E.S	
25 c)	Vehicles bodies must not be prone to changing shape due to wind and must not include any external appendages that might be dangerous to other team members.	S.1 Body	M.H.S P.T.L A.B.E	
25 d)	The vehicle interior must not contain any objects that might injure the Driver during a collision	S.3 interior S.2 Driver	E.S M.H.S	
25 e)	Windows must not be made of any material which may shatter into sharp shards. Recommended material: Polycarbonate.	S.1 Body	M.H.S P.T.L A.B.E E.S	

1.2.-Chassis/ Monocoque Solidity:

Article	Requirements	System	Responsible	Status
26 a)	Team must ensure that the vehicle chassis or monocoque is solid	S.1 Body	Ø.S. P.T.L	
26 b)	The vehicle chassis must be equipped with an effective roll bar that extends 5 cm around the driver's helmet when seated in normal driving position with the safety belts fastened	S.1 Body S.3 Interior	Ø.S P.T.L	
26 c)	This roll bar must extend en width beyond the driver's shoulders when seated in normal driving position with the safety belts fastened. A tubular or panel type roll bar can be used.	S.1 Body S.3 Interior	Ø.S	
26 c) i)	If a tubular roll is used it must be made of metal	S.1 Body S.3 Interior	Ø.S	

Appendix II: Architectural design



Appendix III: Risk Management

The System Engineering team used Google docs to save and keep track of the risks for each subsystem. Google docs. was used because it gives the opportunity to share the document with all team members and this allows team members to make the changes that they want.

An example of a Google Doc sheet is represented in this appendix, the S.5 Front suspension is used as example. The same as represented for the S.5 Front Suspension was done for the rest of the subsystems and also for the project management. The risks were evaluated each week until the risk value reached a really high value and the System Engineer saw that there was not decreasing.

In the example, it can be seen how the risks were divided into technical and resource. The risks were defined, linked to parts of the subsystem and weighted. Then a mitigation strategy was developed. It can also be seen that the status of the risks could be change and that each risk was allocated to team members.

System			Technical				Resources				Comments	Mitigation plan	Status	Responsible	Resources	Comments
			Risk	L	C	Lx C	Risk	L	C	Lx C						
S.5 Front suspension														AQ/HS		
	S.5.1	**Linkages**	Misalignment	2	4	6					Higher rolling resistance and greater wear on tires and mechanical links	Fine tune alignments		AQ/HS		
			Rods may bend	2	3	5						Use spare		AQ/HS		
			Rods may break	1	4	5						Use spare		AQ/HS		
	S.5.2	**Shock Absorbers**	Ref S.6											AQ/HS		
	S.5.3	**Axle**	Axle may bend	2	2	4					Can't drive or brake disc misalignment	Use spare		AQ/HS		
			Axle may break	1	2	2					Can't drive	Use spare		AQ/HS		
	S.5.4	**Hub**	Lug threads wear out	2	4	8					Can't attach wheel	Tape over 2nd set of lug bolt holes, then after damage: use 2nd set of lug threads on same component		AQ/HS		
			Brake disc threads wear out	1	4	4					Can't brake or pass inspection	Use 2nd set of threads on same component		AQ/HS		
			Retaining ring groove creeps	1	3	3					Retaining rings can't cage bearings, but there will still be enough friction to contain them			AQ/HS		
			Retaining ring fails	1	2	2						Use spare retaining ring		AQ/HS		
	S.5.5	**Tie rods**	Tie rod may bend	1	5	5						Spare		AQ/HS		
			Tie rod may break	1	5	5						Spare		AQ/HS		
			Misaligned	3	3	9						Realign		AQ/HS		
	S.5.6	**Front knuckle**	Delamination on upper swivel bolt	1	3									AQ/HS		
			Lower swivel bolt pull-out and resulting delamination in knuckle	2	5						Should only happen in extreme cases	Glue bolt back in, and try again. Otherwise use spare. Ideally avoid switching to spare, if the knuckle was subjected to adverse loads which cannot be avoided in the future.		AQ/HS		
			Toe delamination	1	4						Should only happen in extreme cases	Glue toe back together and wrap in carbon fiber or perforated strips, depending on the situation.		AQ/HS		
		Acc risks				**58**				**0**						
		Total								**58**						

Average risk		**4,142857143**
Total		Likelihood of success
	Technical	5
	Resource	4

Appendix IV: Mitigation plan

Mitigation Plan:

Subsystem: **S.5 Front Suspension** Responsible: A.Q Date:

Part	Risk	Mitigation plan	Responsible	Status
S.5.5 Tie rods	Misaligned	Realign	A.Q	
S.5.4 Hub	Lug threads wear out	Use 2nd set of lug threads on same component	A.Q	
S.5.1Linkages	Misalignment	Fine tune alignments	A.Q	
	Rods may bend	Use spare	A.Q	
	Rods may break	Use spare	A.Q	
S.5.5 Tie rods	Tie rod may bend	Use spare	A.Q	
	Tie rod may break	Use spare	A.Q	
S.5.3Axle	Axle may bend	Use spare	A.Q	
	Axle may break	Use spare	A.Q	
S.5.4 Hub	Brake disc threads wear out	Use 2nd set of threads on same component	A.Q	
	Retaining ring groove creeps		A.Q	
	Retaining ring fails	Use spare	A.Q	
For all rods	Threads could fail	Spare	A.Q	
For all spacers	Could lose	Spare and storage	A.Q	

Appendix V: Assembly test

This appendix will give an example of the SE work during the testing phase. A system integration report of the mechanical parts will be presented as an example. Due to space requirements just the mechanical report has been linked in the Thesis.

System Integration test Report SysTR: Mechanical Parts

Section 1: Scope

1.1 Identification.

The subsystems that will be integrated in this test report are the mechanical subsystems that the car consists of.

S.1 Body, S.2 Interior, S.5 Front Suspension, S.6 Rear Suspension, S.7 Wheels, S.8 Brake system, S.12 Steering

1.2 System Overview.

The subsystems that integrate this report are mechanical subsystems that will be tested to check how they perform when assembled together.

The test will take place in a non-aggressive environment where the results of the tests are not going to be compromised by environmental conditions. Hence, the results will show the subsystems and interfaces performance. Once, the tests in a non-aggressive environment have been performed the testing place will be moved to a more demanding environment.

The test will check Shell Requirements' that are linked to the assembly of different parts.

Each responsible of the subsystem is the stakeholder of these tests, and above all, the SEM team.

1.3 Document Overview.

This document will show the reader the tests that were performed in order to check that the mechanical subsystems worked correctly and specially the interfaces between those subsystems.

Section 2 Referenced Documents

Documents that are linked to this report: Google doc: Assembly test

Section 3: Overview of Test Results

The result of the tests as well as the test procedures, personnel, material, status requirement for passing and comments were displayed in Google docs so every team member could add more test or have an overview of the test that were going to be performed.

In the following pages the Brake system and Steering subsystems will be used as an example to show how the Google docs were.

System Integration Test Description: SysTD

Subsystem: ***S.8 Brake circuit*** **Responsible:** H.J.S **Test Date:** 19.04.2012 **Place:** Dragvoll Sport center

Test no.	Test ID.	Procedure	Requirement for passing the test	Personnel	Material/ Tools	Performance (measures)	Comments	Status	Correcting actions
1	Effectiveness of the braking circuit	Place the car on a 20%slope.	The vehicle must remain stationary.	Driver and team member pushing the car		The car must remain stationary	The car remained stationary and then it was also pushed while the braking.	Pass	
2	Braking capabilities	Move the vehicle and test the brakes	Enough brake force	Driver and team member pushing the car				Pass	
3	Leaks	Press hard on brake pedal	No visible leaks	Driver and team member to check if there are some leaks	Entire Brake system	No visible leaks have to appear		Pass	

4	Brake pedal dimensions	Measure the dimensions	Minimum surface area of brake pedal: 25 cm2.	One team member to measure it			The Brake pedal is approximately 49 cm2	Pass	
5	Braking effectiveness	Combinations of weak, gradual, hard and instant braking with low and higher speed, as well as during turning at different radius.	The brakes must be strong enough and have to stop the car as soon as the driver steps on the pedal	Driver and another team member to push the car and to measure the distance		The brake systems must be reliable and able to perform		Pass	

Braking:

Initial braking should be cautious to listen to how the brake pads attack the discs, and the vibrations that are transferred to the chassis and amplified.

We should try combinations of weak, gradual, hard and instant braking with low and higher speed, as well as during turning at different radius.

We will also need to check whether the rear wheels begin to skid (if allowed by the gym center) - if they do, too much force is routed to the rear brakes.

Subsystem: **S.12 Steering** Responsible:H.J.S **Test Date:** 19.04.2012 **Place:** Dragvoll Sport center

Test no.	Test ID	Procedure	Requirements for passing the test	Personnel	Material/Tools	Comments	Status Pass/ No pass	Correcting actions
1	No excessive play	Turn steering wheel	Wheels should not rotate more than 3 deg. before the draglink moves.	Driver and team member to push the car			Pass	
2	6 m turning radius	Roll the car and turn max.	The turning circle must be less than 6m radius (at max load)	Driver and team member to push the car	Ruler		Pass	
3	Turning	Mark the turning course. Also have to observe for roll due the softness/stiffness of the springs	turns must be pleasant	Driver and team member to push the car	we need to bring some ruler and markers, e.g. PVC tape or soda bottles to	The driver had no input on when and where the maximum steering was achieved	Pass	An end point was mounted on the steering so the river will know when the maximum steering has been reached

4	Steering alignment:	we will have to roll and listen for any screeching during straight ahead and turning, and then try to adjust.	No screeching	Driver and team member to push the car			Pass	
5	Turning capability: Other tests include gradually increasing and decreasing curves (to approach static equilibrium) as well as jerky steering to see how well the steering responds, and how much the car dives on the outer front wheel of the curve being entered.	Place some cones on a straight line with a quite big separation among them. Drive the car in zigzag through the cones. Reduce the distance between the cones.	The car must be able to pass the track without any problem	Driver and a team member to push the car	Cones	The pulley mounting points came off when the turning was more demanding	After first testing day the status is not passed. Second test day status: Pass	The contact area of the pulley with the body will be increased and glued again.

Appendix VI: Performance test

System Qualification/Acceptance test report.

Section 1: Scope

1.1 Identification.

The tests will be performed to the whole system that is the DNV FF2. The tests performed will be Black-Box testing since the importance will be on the functionality.

1.2 System Overview.

The DNV FF2 is formed by 12 subsystems, some of these are mechanical, some electrical and cybernetic and then there is a human subsystem that is the driver.

The tests will try to study the functionality of the system as a whole.

The tests were performed at Dragvoll's parking lot, the team also got the Trondheim Harbor but due to schedule problem and weather conditions this place was not used.

The acceptance tests will also be done in Rotterdam.

1.3 Document Overview.

This report will show the tests that were performed in order to check DNV Fuel Fighter 2's functionality and operation capabilities.

Section 2 Referenced Documents

SysTD of the performance test saved in Google docs. Example of SysTD displayed in this Appendix

Section 3: Overview of Test Results

The results of this test phase are presented in the SysTD in order to give an idea of the expected outputs that were defined and if those outputs were achieved or not. The SysTD also shows the corrective actions that were done if the expected output was not met.

System Qualification/ Acceptance Test Description. SysTD

Place: Dragvoll Parking Lot **Date** 11.05.2012 **.Personnel:** B.G/ I.Y.G/ O.T

Test no.	Test ID	Procedure	Expected Output	Status	Comments	Corrective action
1	Test the old rims	Drive the car with the old rims and also with combination of new and old rims	The rims will behave well	Pass		
2	Rolling	Put the car up to different speeds and see how far/long it continues to roll, maybe even vary the weight to see how much the tire rolling friction is influenced. Rolling at higher speeds. Check if any wheels lift off the ground		Pass		
3	Braking	Try combinations of weak, gradual, hard and instant braking with low and higher speed, as well as during turning at different radius. Put the car into the maximum speed and brake. Measure the distance needed to stop the car	The braking capacity will be enough	Pass	The brake system behave really well braking at maximum speed in a short space	
4	Braking	Check whether the rear wheels begin to skid if they do, too much force is routed to the rear brakes.	Reduced skidding	Pass	There was a bit of skidding when the braking was extreme	No need
5	Cornering	How fast can we take the corners? How much speed we lose	The car will turn at 25km/h	Pass	The car could corner much faster, 30 km/h. The speed loss in really low 2-3 km/h	

6	Wet Braking	See the effectiveness of the brakes when they are wet.	The brakes will be able to stop the car	Pass		
7	Rear suspension	Study the behavior of the suspension when turning, braking and with realistic bumps	The suspension must support the old engine's weight	Pass	The road conditions in Dragvoll are harder that in Rotterdam	
8	Steering radius	Check the turning radius.	The driver must feel comfortable cornering into 90 degree turns	Pass		
12	Coasting	Coasting capabilities	The car must be able to coast for quite a long time. (No distance can be defined)	Pass	In Rotterdam it was shown that coasting capabilities are outstanding	
13	Damping	Checking the dumping capabilities is a bumpy road as Dragvoll's parking lot	4 wheels must touch the ground at all times	Pass		

Appendix VII: Acceptance test review

Acceptance Test Reviews are performed after each test. It is an informal approach to the results of the tests. In this appendix an example of an Acceptance test review is shown, it was done after the race test in Rotterdam to the responsible of the cybernetic part of the vehicle.
The System engineer asks some questions linked to performance to the engineer.

Once the race is over:

- **Which extra tests should have been done?**
  - Both batteries should have been tested
  - white battery should have been tested for smaller engine air gaps, too, in order to find minimum aid gap for each battery
  - fly start routine at higher speeds and torque

- **Which test should have been improved? (if any)**
  - test procedure works – counter torque adjustment for different loadings can be improved by using a counter engine instead of resistors

- **Why those tests were not made? (Time/lack of knowledge…)**
  - test could not be performed because of a time lack especially due to the fact that the test bench is located at a sponsor and thereby not available all time

- **What could have been avoided by doing those tests?**
  - Test runs could have been used in order to optimize engine controller parameters for a better result

- **Lesson learned**
  - test of all relevant drive train parameters should have highest priority
  - more time for testing has to be spend
  - in house test bench for power train is needed