Master Thesis Work

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« Modeling of a Spark Ignition Engine Systems Architectures »

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Abstract

This work is the result of a six months internship at Groupe Renault at the technical center of Lardy (91 Essonne, France) within the Systems Engineering Department, from 15th of February to 14th of August 2019, in order to obtain the European Master in Automotive Engineering degree and the Engineer Degree from ENSTA Bretagne.

The Systems Engineering Department presents the strategies decided by the company for the Alliance Renault-Nissan-Mitsubishi powertrain control system. These strategies are represented in several documents as systems architectures. Those documents illustrate the requirements and functionalities electromechanical systems and are presented to the Software Department in order to build the software integrated in the Engine Control Unit (ECU) and also to the Components Department in order to develop new mechanical components.

The main purpose of this project was to provide functional and physical architectures support for powertrain control systems while insuring the coherence between all the systems concerned.

Keywords: Systems Architectures, Functional architecture, Physical architecture, requirements, Model-Based systems engineering, Powertrain, Spark ignition engines, ECU

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List of Abbreviations and Acronyms

ADC	Air Distribution to Cylinder
ASG	Air System Gasoline
CTU	Czech Technical University
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EMAE	European Master in Automotive Engineering
ENSTA Bretagne	Ecole Nationale Supérieure de Techniques Avancées Bretagne
FBS	Functional Breakdown Structure
INCOSE	International Council on Systems Engineering
MBSA	Model-Based Safety Assessment
MBSE	Model-Based Systems Engineering
NEDC	New European Driving Cycle
PBS	Physical Breakdown Structure
RDE	Real Driving Emissions
SCDR	System Control Design Review
SDD	System Design Document
STR	System Technical Requirement
SysML	System Modeling Language
UML	Unified Modeling Language
VVT	Variable Valve Timing
WLTP	Worldwide harmonized Light vehicles Test Procedures

Introduction

With the high complexity that our industries deal with and the more and more constraining requirements of our society, it becomes nearly impossible to develop a product or a process without a clear view of all stakeholders bringing their needs and requirements. Therefore, systems engineering becomes a necessity in all industries while developing a product. It considers both the technical and the business needs and leads to achieving the goal of providing a product with the quality that the final user would expect. One can find Systems Engineering in every industry. Systems Engineering enable a different approach to overcome the high complexity of today's systems called **model-based systems engineering (MBSE)**. Therefore, systems engineering makes all the engineering fields to interact during the whole cycle in order to converge on different specifications.

In this context, Mechanical Division in Groupe Renault builds its systems architectures around the powertrain to detail its functionalities but also to allow a study of risks by the **dependability** team. The main goal of this project was to **provide systems architectures of a spark-ignition engine** as a support for the different systems (teams) of the department. The different tasks were:

- **Functional architectures**
- **Physical architectures**
- **Traceability** highlighting

This work presents in detail the interest of the model-based systems engineering regarding the provided documents for communication, design, calculation or software generation purposes. This master thesis proposes to study the concept of MBSE in application in the automotive industry, especially in the powertrain control systems.

The first chapter presents the concept of Model-Based Systems Engineering itself by presenting the different objectives of this area and the different architectures that can be found in a system modeling.

The second chapter presents the work done at Groupe Renault in the Systems Engineering Department and describes the methodology put in place. It settles the context of the automotive industry regarding emissions standards in Europe and clarifies the purpose of Model-Based Systems Engineering, its methods and its operation. One example will be taken as the system leader of this project before introducing to the inter-systems modeling.

The third and last chapter of this project presents the **results** of the previous work and gives an interpretation of them. It also presents the possible extension of the MBSE modeling, especially to the Model-Based Safety Assessment (MBSA).

Chapter 1 – Model-Based Systems Engineering

1.1. Systems Engineering

1.1.1. Origins

One can trace the beginning of systems engineering from the 1960s in the US with the development of spatial and military programs by a couple of agencies: NASA (National Aeronautics and Space Administration) and USAF (United States Air Force). A couple decades later, following a high number of systems failures, often due to imprecise specifications, ignored requirements, non-validated solutions or confusion of responsibilities between two actors, institutions decided to pay more attention to the upstream development and therefore the systems engineering. It is in that case that the **International Council On System Engineering** (INCOSE) was created in 1991. This organization shares the process of systems engineering with the rest of the world in order to respond to general issues implicating several areas of expertise. [1]

1.1.2. Presentation

It is fundamental to give few definitions about systems engineering because one can find different definitions and therefore get confused. According to the INCOSE:

" Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Performance, Test, Manufacturing, Cost & Schedule, Training & Support, Disposal" [2]

This definition gives the framing of the studies: the systems engineering begins from the top of the cycle but can be found in the validation part as well. From the beginning of the studies, all the areas of expertise are involved in the process of systems engineering.

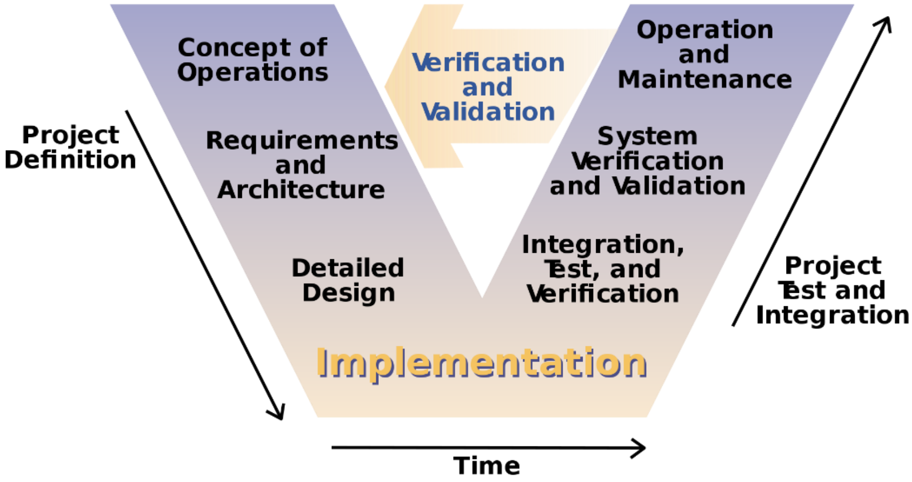

Figure 1: V-Cycle development for Systems Engineering

The figure 1 illustrates the V-cycle for the development of a product. Once the requirements are collected by the systems engineering team, the systems architectures are made. From these architectures, the product can be designed, integrated, tested and verified before final validation.

1.1.3. Purpose of Model-Based Systems Engineering (MBSE)

Systems Engineering regroups several engineering fields that often create models in order to represent their systems. These models are therefore at the center of their work. Their nature can differ, but their representations are often similar. The systems engineer use a modeling language that defines the rules of modeling (syntax, structure, semantics, etc...). One of the most widespread languages is the SysML which is described in the following section (1.2.2).

MBSE can be defined as "a*n approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition life cycle."* [3]
Thus, MBSE is a mean to perform Systems Engineering. Indeed, the Model-Based Modeling represents the system studied in its environment during its operational phase. It shows how it operates in order to satisfy all the stakeholders' requirements.

A **Stakeholder** can be described as an actor, individual or a group, that is directly or indirectly, impacted by the execution of a system. [1] Thus, the stakeholder can submit requirements to the system studied and the latter must adapt its operations to meet these requirements.

In Systems Engineering, the model used to represent the system are usually the systems architectures. Their main goal is to present (diffuse) how the system works by highlighting the strategy retained by the engineers. Depending on the objective of the model, one can choose one diagram or another.

One of the main advantages of the MBSE is the possibility to **detect defects** earlier in the cycle. Indeed, if any defect is detected prior the phase of industrialization, the cost of the correction will be much less important than otherwise. So, the analysis of the model will play a big part of the success (financial and technical) of the project.

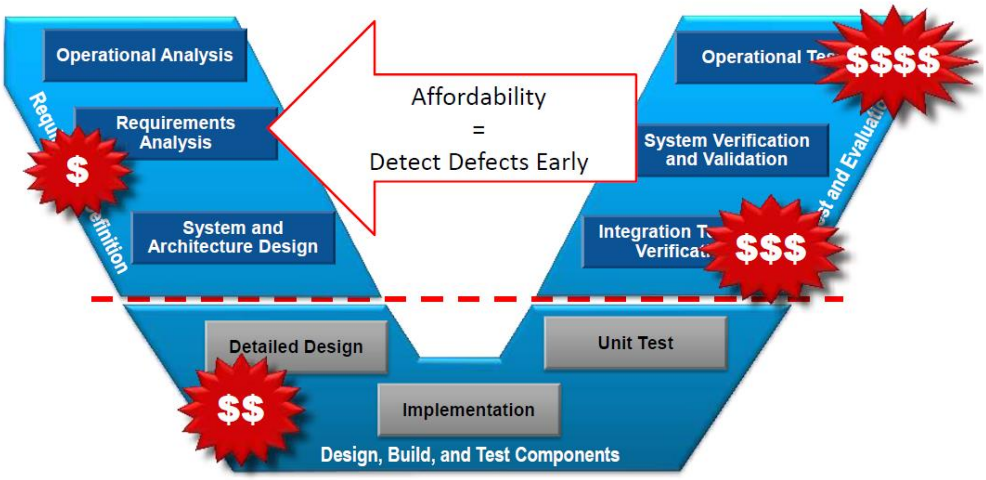

Figure 2: Advantage of MBSE: detect defects earlier [4]

This Figure 2 illustrates this advantage of MBSE regarding the defaults detection earlier in the development process. The Model-Based System Engineering makes the development more affordable.

1.1.4. Process of MBSE

As one can easily imagine, the key element of a MBSE approach is the modeling goal. Once it is defined, it is necessary to:

- follow a modeling method
- choose a language
- choose an adapted tool

This is summarized in the following figure 3:

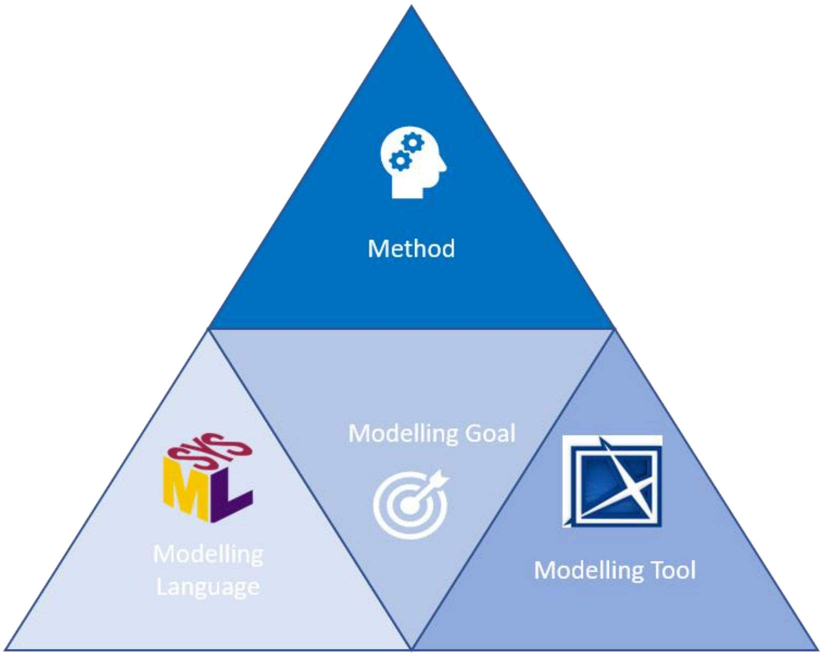

Figure 3: Outline of MBSE Modeling

One can give a more detailed process of system modeling. Usually, the process starts with the **reception of requirements** coming from the environment (stakeholders) before analyzing the system itself (identifying subsystems, functions and components). It is important to identify use cases and demonstrate how the system should behave or respond regarding these use cases with some simulation or calculation if necessary. Once the stakeholders' requirements received and the system analyzed in function, the system engineer cans start breaking down these requirements to the subsystems before building the final subsystem specification.

The Figure 4, inspired by an INCOSE presentation, describes this process in detail. The figure, which has been generated using a system modeling language (SysML), is a good example that MBSE can be very useful to present a process. We will see further in this document few architectures that are generated using the same modeling language.

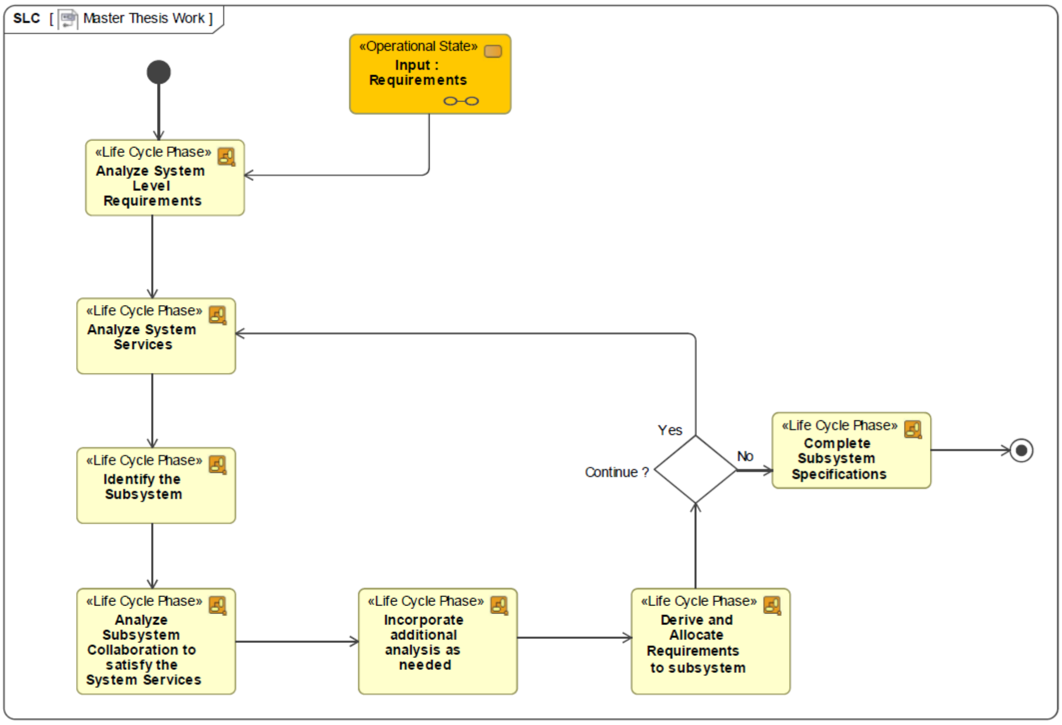

Figure 4: System Decomposition Process [4]

1.2. Systems Architectures

1.2.1. Purpose

A System architecture is a representation by models describing a system. It is quite clear that it would be very difficult to design a system without knowing how it is structured and how its components are integrated. The system architecture, which is considered from three main viewpoints described in the following section, helps to understand the operation of a system, its functions shows the integration and the use of all the components.

Systems architectures have two main goals:

1) It represents a solution of architectures which means it describes all the key elements of the system (functions, components, sub-systems, interface, flows, software, etc…) and how these elements are organized and assembled with each other. Systems engineers use the three viewpoints available in MBSE to give these representations.

2) The second goal is to interact with technical and transversal domains in order to have a feedback on these solutions and adapt its structure to meet all the requirements and constraints.

The Figure 5 is translated from AFIS website, the French association of Systems Engineering. [5]

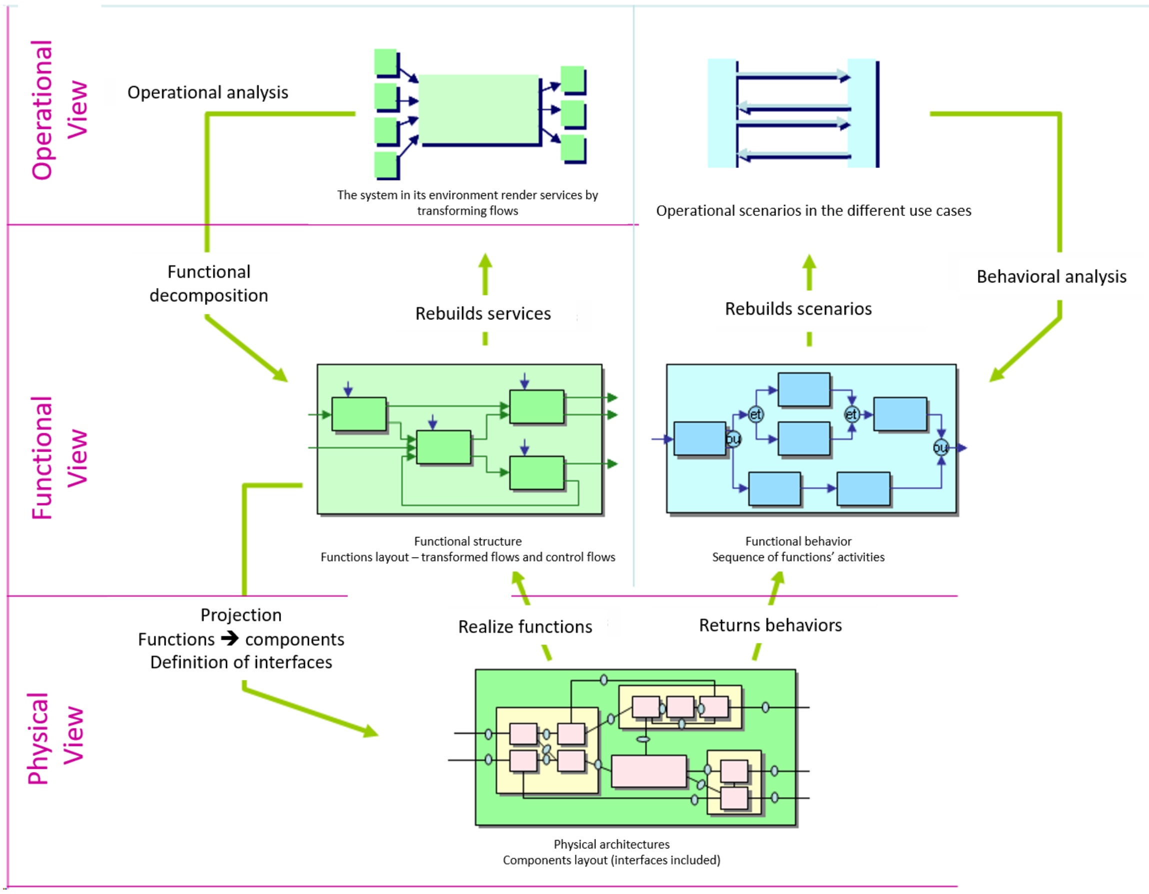

Figure 5: The 3 viewpoints of Systems Architectures

1.2.2. SysML

SysML (System Modeling Language) is an improved language from UML (Unified Modeling Language) which includes 9 types of diagrams. SysML is used in Systems Engineering to facilitate the collaboration of several actors from different work domains around a common model to define a system. It is a great way to centralize all the different documents (requirements, constraints, etc..) and keep the model updated in order to ensure a coherence and to respect the system specifications. This language is independent from a modeling methodology or a modeling tool.

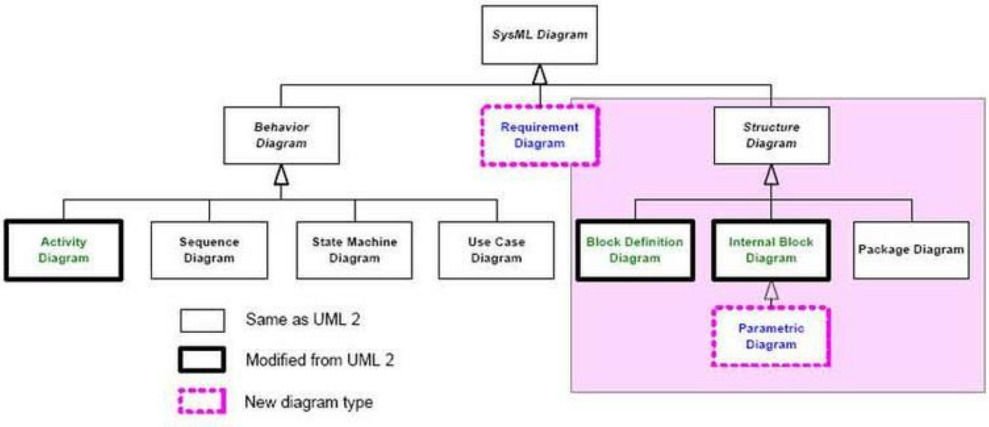

Figure 6: SysML diagrams and evolution from UML

SysML offers several benefits:

- Centralization and sharing of all the specifications of a complex system between all the actors
- Identification of the risks and creation of a common base of analysis
- Improvement the project managements during the entire life cycle of the system
- Generation of several documents for different work areas [6]

It also gives a semantics which indicates a signification for every modeling element (connectors, blocks, symbols, etc…) and a notation which gives a representation of this signification. SysML relies on 4 pillars:

- Structure (*block definition diagram, internal block diagram*)
- Behaviour (*activity diagram, sequence diagram*)
- Requirements (*requirement diagram*)
- Parametric (*parametric diagram*)

The following figure gives examples of previous diagrams.

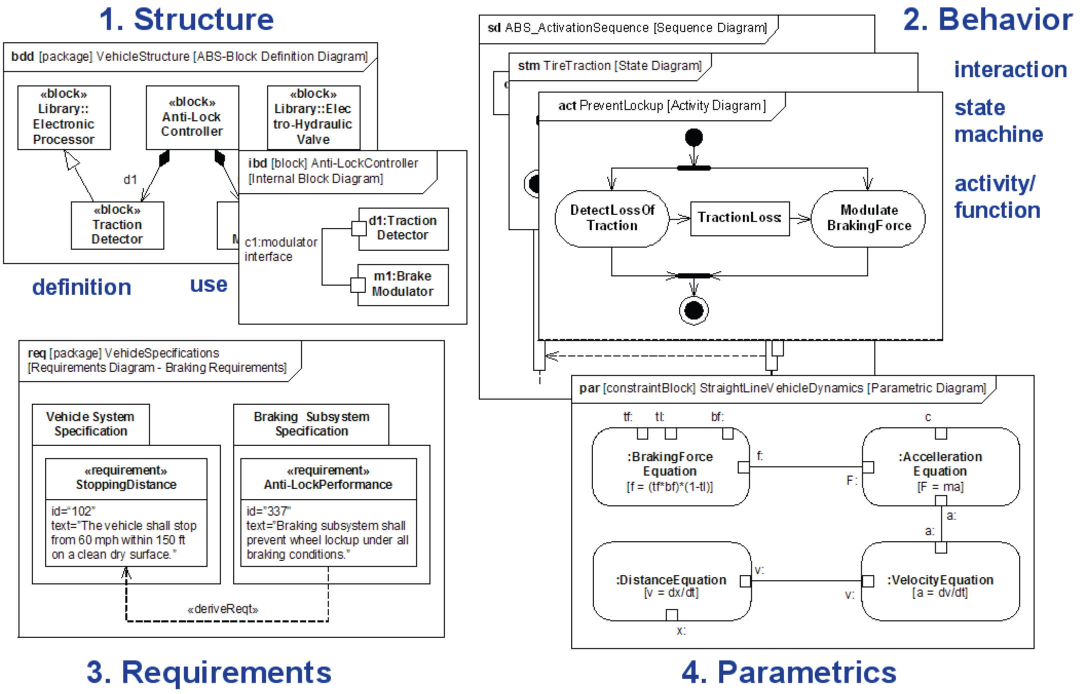

Figure 7: Four SysML pillars and main diagrams [7]

1.2.3. Functional Diagrams

The functional architectures, from the functional viewpoint, are one of the most used diagrams. The main purpose of a functional diagram is to represent the functional operations of the system. It must show exhaustively all the flow exchanged by the system and its environment, in every layer of the system (subsystems, functions, sub-functions, …). As it is indicated in the figure 5, it describes functional structure. All the functions are represented and structured in the sub-system owner. This decomposition can be made from the operational analysis.

Before modeling a functional architecture, it is useful to create a **Functional Breakdown Structure** (FBS) where all the functions are mentioned and structured. In this type of document, one can easily show the dependence and owning relations between functions and sub-systems. It is usually represented as a hierarchical tree for better comprehension, while respecting modeling rules from SysML ("direct composition" relations between functions), as the following figure shows.

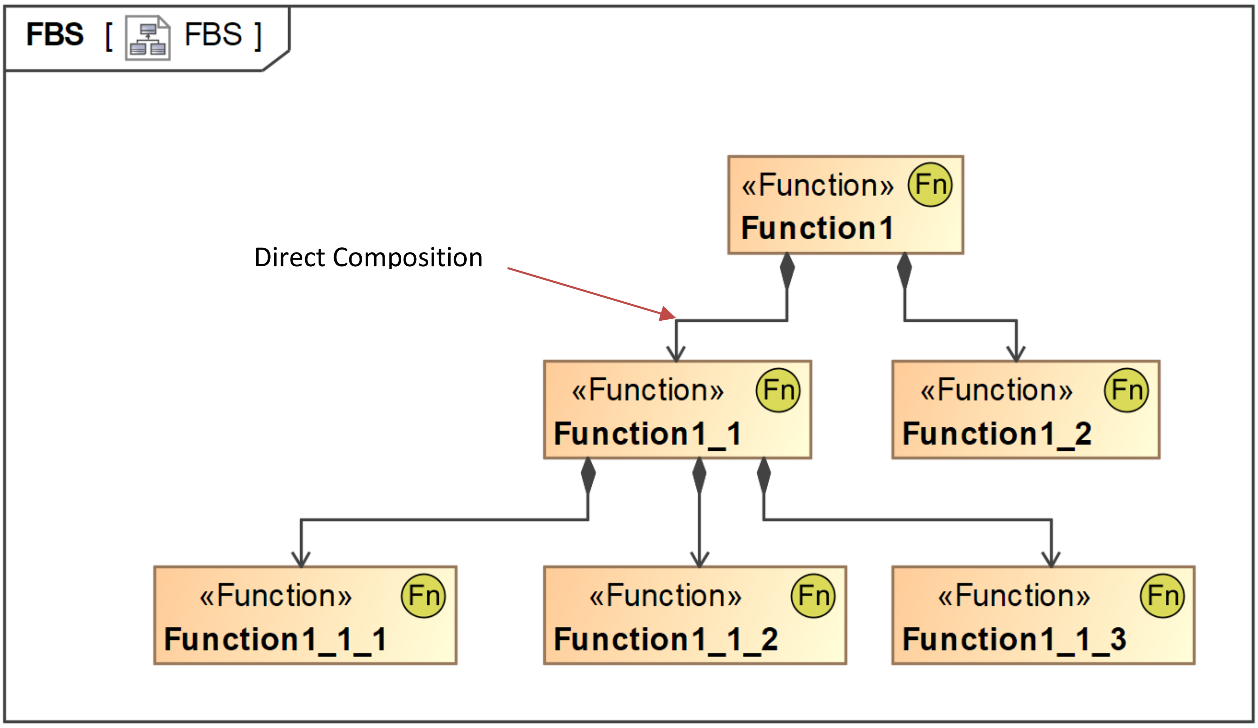

Figure 8: Example of a Functional Breakdown Structure

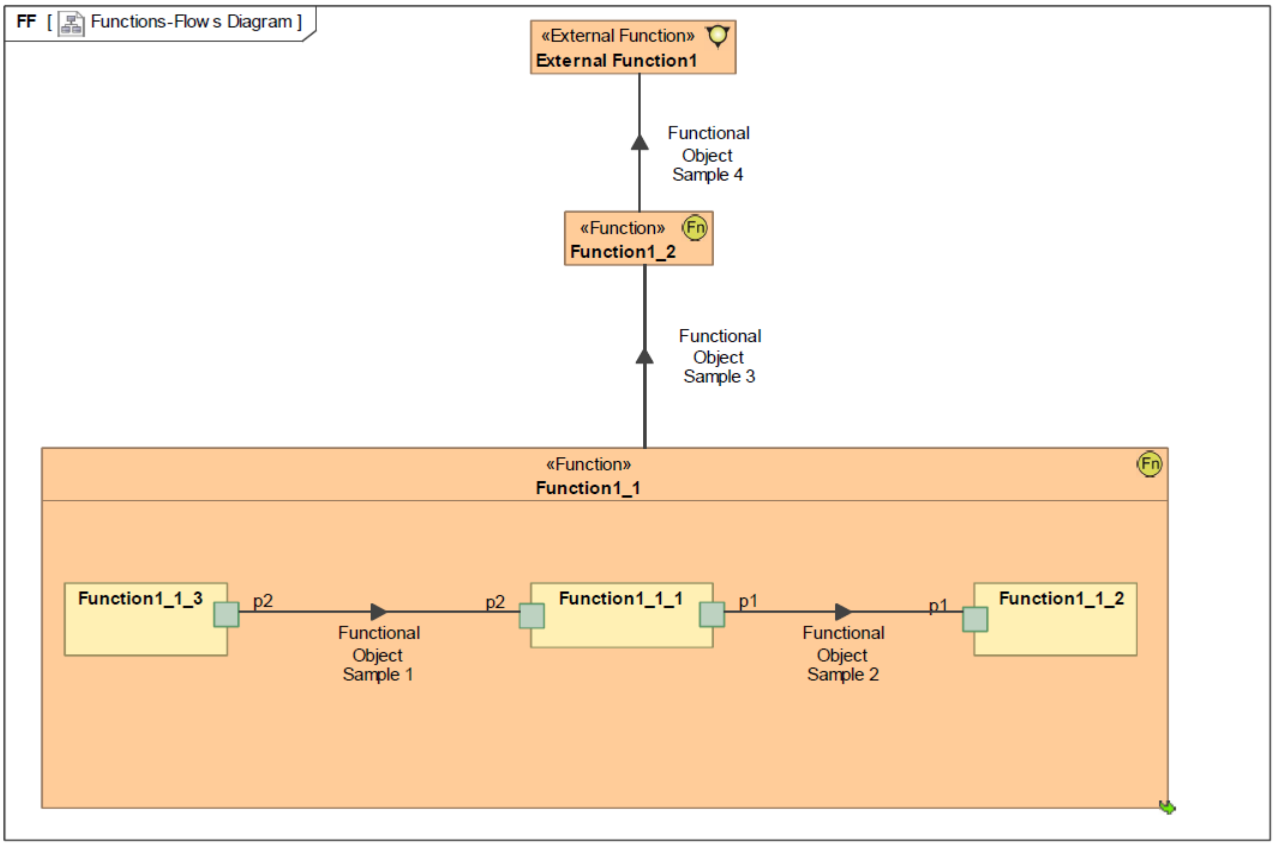

Figure 9: Example of a Functional Architecture

1.2.4. Physical Diagrams

The physical diagrams are quite like the functional architectures. The only difference is that the principal objects represented are components and not the functions. The main purpose of the physical architectures is to present the decomposition and the structure of all components that constitute the system with all the physical flows (usually flows of matter and/or energy) that are exchanged between components. The physical diagrams can be a good mean for communication purposes because they represent clearly which component realize the functions and how they communicate to make the system work.

Like the functional architectures, the physical architectures can be accompanied by a **Physical Breakdown Structure** (PBS) where one can find all the components of the system (or the sub-system) and the detailed structure. In this document, the system engineer can represent the sub-components that are not usually shown in a generic representation of the system.

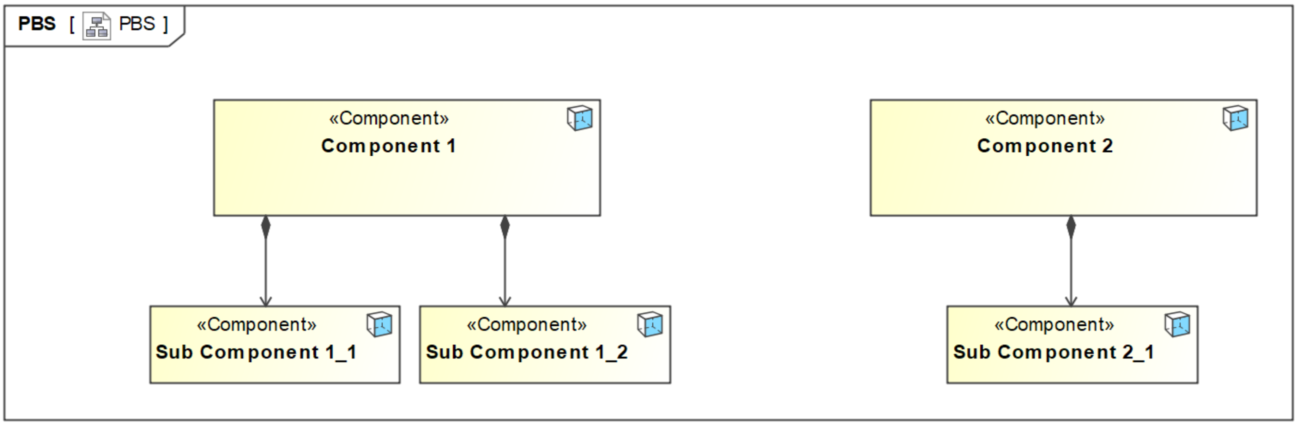

Figure 10: Example of a Physical Breakdown Structure

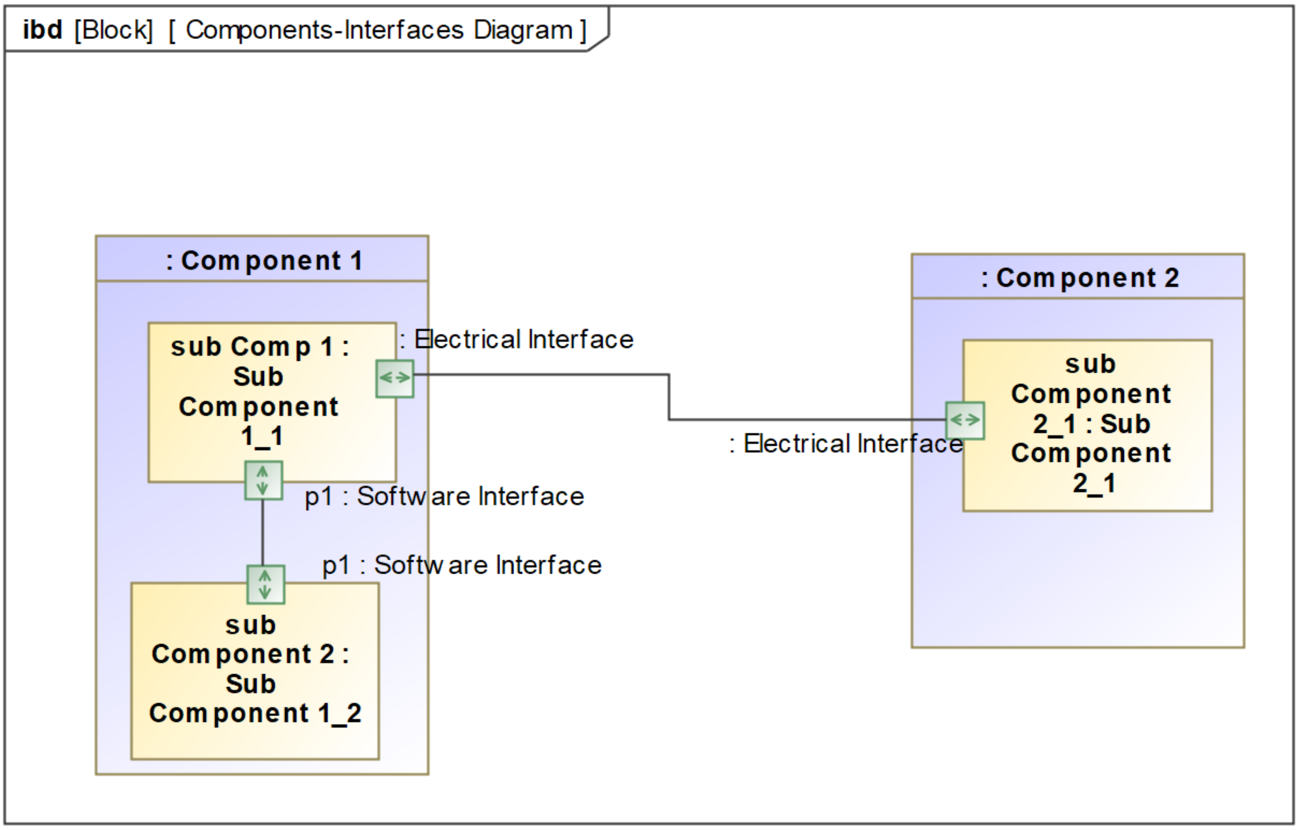

Figure 11: Example of a Physical Architecture

Summary

To conclude this chapter, Systems Engineering is a very important engineering discipline. It intervenes throughout the V cycle. It relies on Model-Based Systems Engineering (MBSE) to define the system and to create models that represent the latter. MBSE has many advantages and one of them is the possibility to detect defects early in the development cycle. Indeed, MBSE modeling involves several technical areas but also other disciplines from the beginning of the development process. In order to do that, systems engineers use several architectures to represent different viewpoints of the system. MBSE is generally based on three main viewpoints: operational, functional and physical. Each view gives a perspective of the system and they complete each other.

Chapter 2 – Systems Architectures for the Renault Powertrain Control Systems

2.1. Renault Powertrain Control Systems

2.1.1. European Emissions Standards

With the ecological situation in the world and the sad previsions regarding emissions, the quantity of pollutants emitted by the industries are closely checked. This is omnipresent in the automotive industry. Regarding the market where the vehicles are sold, the car manufacturer must limit their car's emissions accordingly. This thesis tackles the Renault's engine for the European market, so we will focus on European Emissions Standards.

The following figures summarize the worldwide regulation overview for 2020-2025. Both cycles, RDE and WLTC, are represented in these two images. To give a comparison, the American Emissions Standards are also given. The values for Euro7 standards are hypothetical.

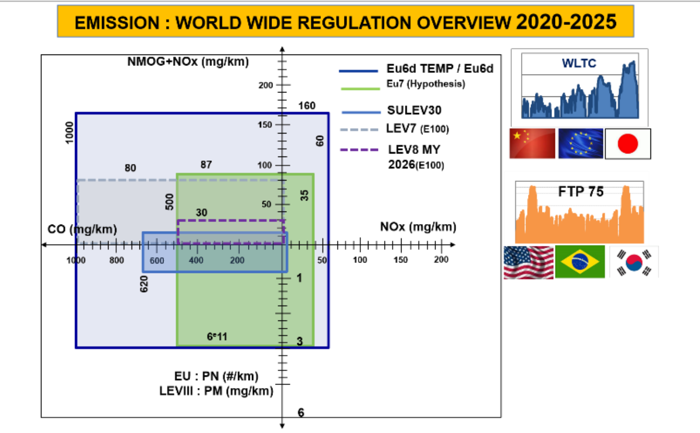

Figure 12: Worldwide regulation overview 2020-2025

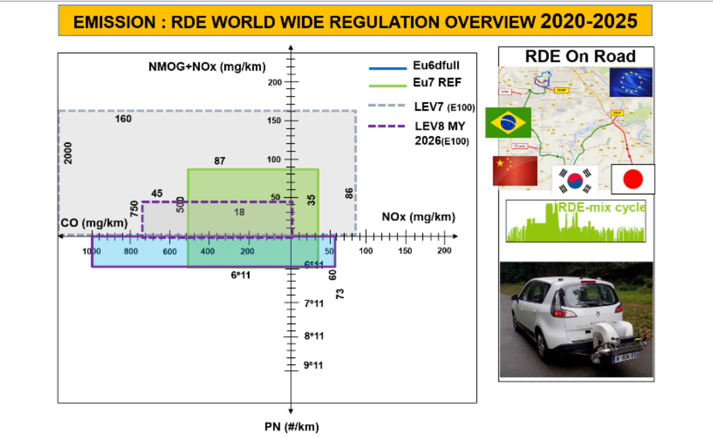

Figure 13: RDE Worldwide regulation overview 2020-2025

Tier	Date (Type Approval)	Date (First Registration)	CO	THC	NMHC	NO_x	$HC+NO_x$	PM	PN [#/km]
Diesel									
Euro 5a	September 2009	January 2011	0.50	-	-	0.180	0.230	0.005	-
Euro 5b	September 2011	January 2013	0.50	-	-	0.180	0.230	0.0045	6×10^{11}
Euro 6b	September 2014	September 2015	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6c	-	September 2018	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6d-Temp	September 2017	September 2019	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Euro 6d	January 2020	January 2021	0.50	-	-	0.080	0.170	0.0045	6×10^{11}
Gasoline									
Euro 5a	September 2009	January 2011	1.0	0.10	0.068	0.060	-	0.005**	-
Euro 5b	September 2011	January 2013	1.0	0.10	0.068	0.060	-	0.0045**	-
Euro 6b	September 2014	September 2015	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}***
Euro 6c	-	September 2018	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}
Euro 6d-Temp	September 2017	September 2019	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}
Euro 6d	January 2020	January 2021	1.0	0.10	0.068	0.060	-	0.0045**	6×10^{11}

** Applies only to vehicles with direct injection engines
*** 6×10^{12}/km within first three years from Euro 6b effective dates

Figure 14: Table of European Emissions Standards for passenger cars. Source: Wikipedia [8]

One of the most important part of the emissions monitoring is the test cycles that all manufacturers must pass if they want their products being sold in Europe. In the former past, knowing the cycle and the pollutants tested, most of the car manufacturers were used to optimize their vehicles emissions only for the cycle. This is what was called the "cycle beating": to get their vehicles authorized, they had only to pass the test. In 2014, few studies were conducted to test the vehicles in real conditions, meaning in traffic. The NOx emissions measured were about six times higher than the Euro6 limits.

Before September 2018, the reference cycle for emissions tests was the **New European Driving Cycle** (NEDC). For more accurate results, this cycle has been replaced by the **Worldwide harmonized Light vehicles Test Procedures** (WLTP) which represent a longer cycle (1800 sec against 1180 sec for the WLTC) and has four “sub-cycles” (against only two for the NEDC).

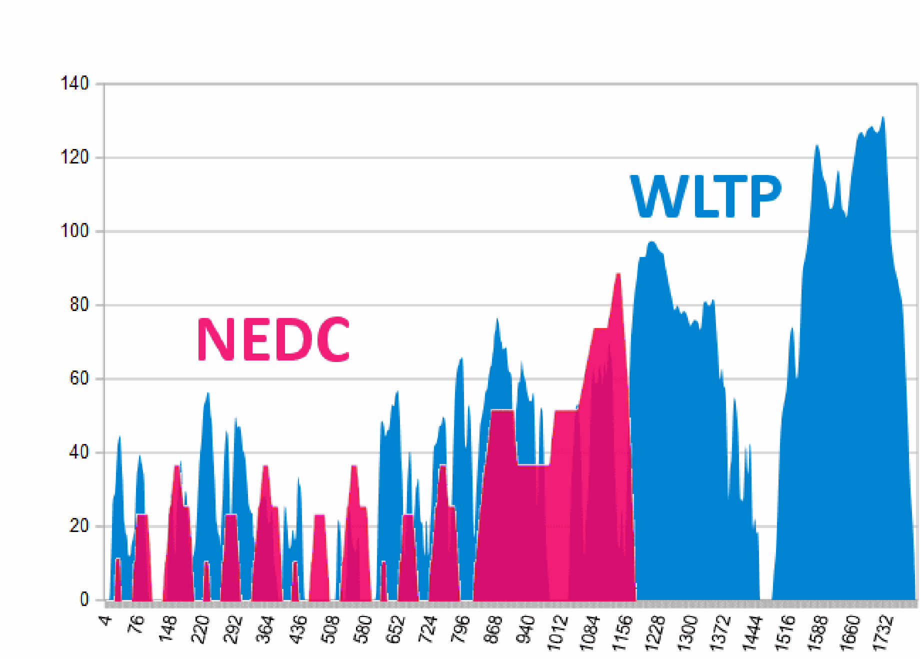

Figure 15: Comparison of NEDC and WLTP [14]

This new protocol is accompanied by another protocol: Real Driving Emissions (RDE). To fight this “Cycle-Beating” tendency, following the 2015 Volkswagen scandal, the European Commission can test random vehicles in real driving situations and measure their pollutants emissions. By changing the testing protocol, most of the car manufacturers saw their emissions increase especially for the premium vehicles where emissions increasing can meet 18%.

The work conducted for this thesis at Groupe Renault fits in this context. Indeed, most of the automotive companies are preparing the futures standards. Therefore, the Renault Powertrain Department is working on the **Euro 7** standards and this document tackles the modeling or systems architectures for the 2023 horizon.

2.1.2. Renault Powertrain Systems

This thesis work has been hosted in the Systems Engineering Department of Groupe Renault at Lardy, near Paris. As described previously, the perimeter of this modeling of Renault's powertrain control systems architectures is Euro 7. As one can imagine, the powertrain is one big system, so it must be divided into several sub-systems. This decomposition will define the structure of the System Engineering Department and so the structure of the teams working on this system. The decomposition retained by Renault was these five sub-systems:

- Air Path System
- Combustion System
- After-Treatment System
- Powertrain Torque Management
- Hybrid Management

One can find other systems in other departments that work with the Systems Engineering Division. For instance:

- Powertrain and Accessories Thermal Management
- Electric Vehicle Charging
- Electric Energy Storage Traction
- Engine Structure
- Gearbox Structure,
- … and many others.

Each system has its own small team with a system architect at the head of the perimeter. The main objective of this work was to model how these five systems communicate with each other and with external systems (stakeholders of the powertrain). Each team has its own modeling, so the biggest challenge was to propose a modeling insuring the coherence of the **inter-system**, as it is described in the following section.

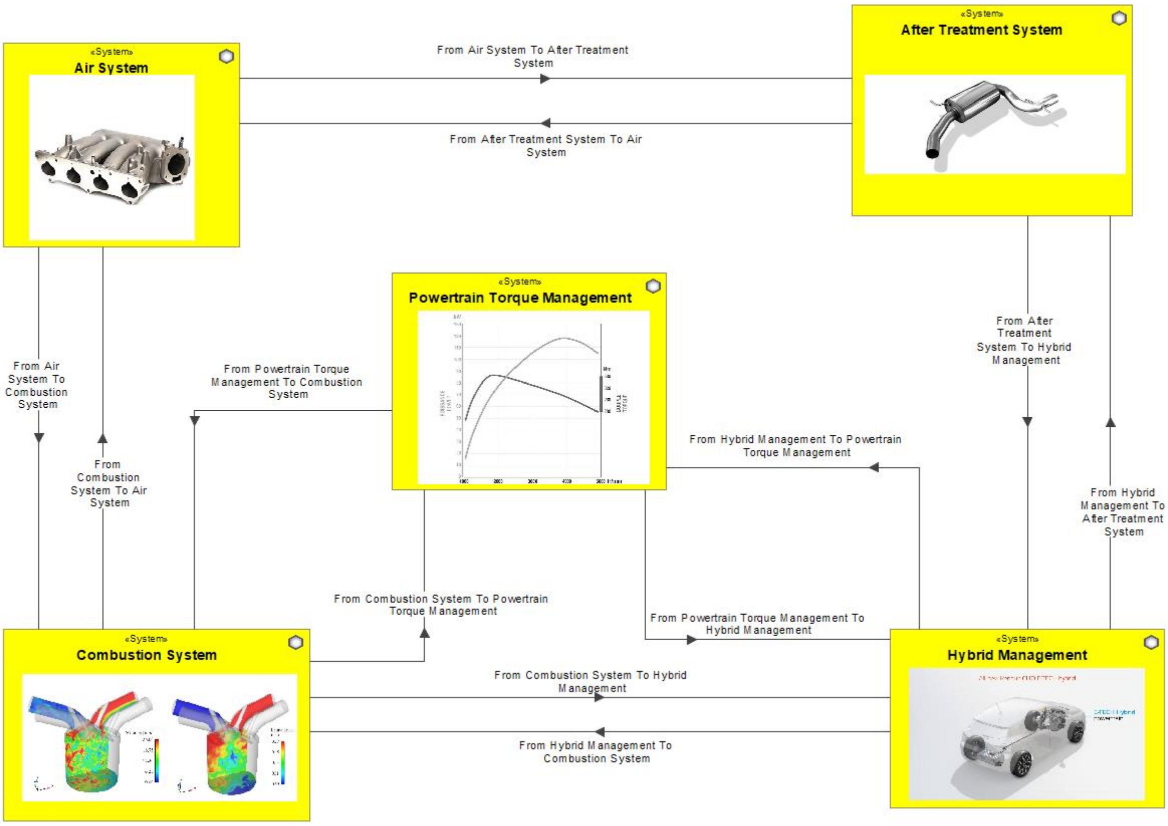

Figure 16: Modeling of the first level of the Renault's powertrain control systems

The following table describes briefly the systems of the department, with the exception of Air System which will be described as the example leader for this project in the next section.

Combustion System	The system's perimeter starts at the top of the cylinder and ends at the exhaust port. It settles all the engine's strategy of combustion and control all the parameters used to optimize the combustion.
After-Treatment System	This system owns components in the exhaust pipe and establish the strategy of after-treatment. It sends requests to other systems to keep emissions as low as possible to always meet the European Emissions Standards.
Powertrain Torque Management	This is the system at the center of the powertrain. It regroups information from every sub-systems and external systems in order to settle the adequate torque regarding the constraints from everyone.

Hybrid Management	Quite young, this system advises the powertrain torque management system in order to optimize the energy consumption from the Internal Combustion Engine (ICE) and the Electric Machine (EM), when it is the case.

Figure 17: Table of Renault's Powertrain Control Systems

This decomposition is valid for gasoline and for diesel engines (ICE alone or with Electric Machine). The only changes that occur are the three first systems (Combustion, Air System and After-Treatment) which differ regarding the type of fuel used. Powertrain Torque Management and Hybrid Management are transversal systems.

2.2. Modeling of Systems Architectures and Methodology

2.2.1. MagicDraw and Modeling Methodology

One of the key steps of the process of MBSE is the choice of a modeling tool. At Groupe Renault, the tool chosen is **MagicDraw**, a SysML based software produced by the company "No Magic" that allows the modeler to represent the system with the three viewpoints detailed previously. One can model systems architectures, perform analysis, generate documents and run constraints solver. With a plugin sold by No Magic, MagicDraw can be used to run simulation of the systems based on SysML.

This tool has been designed to work efficiently with the company's process. Therefore, a special profile has been developed for Renault in order to facilitate the engineers' work. The methodology put in place to model a system is the classical system engineering methodology. There are few steps to go through to obtain a relevant model:

1) First, one should consider the system as a black box: no need to know how the system works or how is it decomposed. One can just focus on the communication with external systems and the environment. Once this step is complete, a list of all inputs and outputs of the global system can be generated. This list is very important because all the inputs of the generic system are the inputs of the sub-systems. So, generating this list is a good way to verify the coherence between the sub-systems.

2) After the list of inputs and outputs generated, one can start focus on the sub-systems. The next layer of the model should be the structure in sub-systems and all the flows exchanged between them. For the powertrain control systems, this view is

represented in the figure 16. As explained previously, the inputs of the generic system should be found in some sub-systems, not necessarily all.

3) The third layer of modeling is the focus on each sub-system. Each Sub-system is decomposed in functions (Functional Breakdown Structure or FBS), illustrated in the figure 8. The purpose of this step is the structuration of all the functions and the representation of the transformed flows between the functions. According to the details level that the systems modeler wants to represent, one can decompose functions into sub-functions for better understanding or for highlighting a specific functionality. The result of this process is the functional architecture.

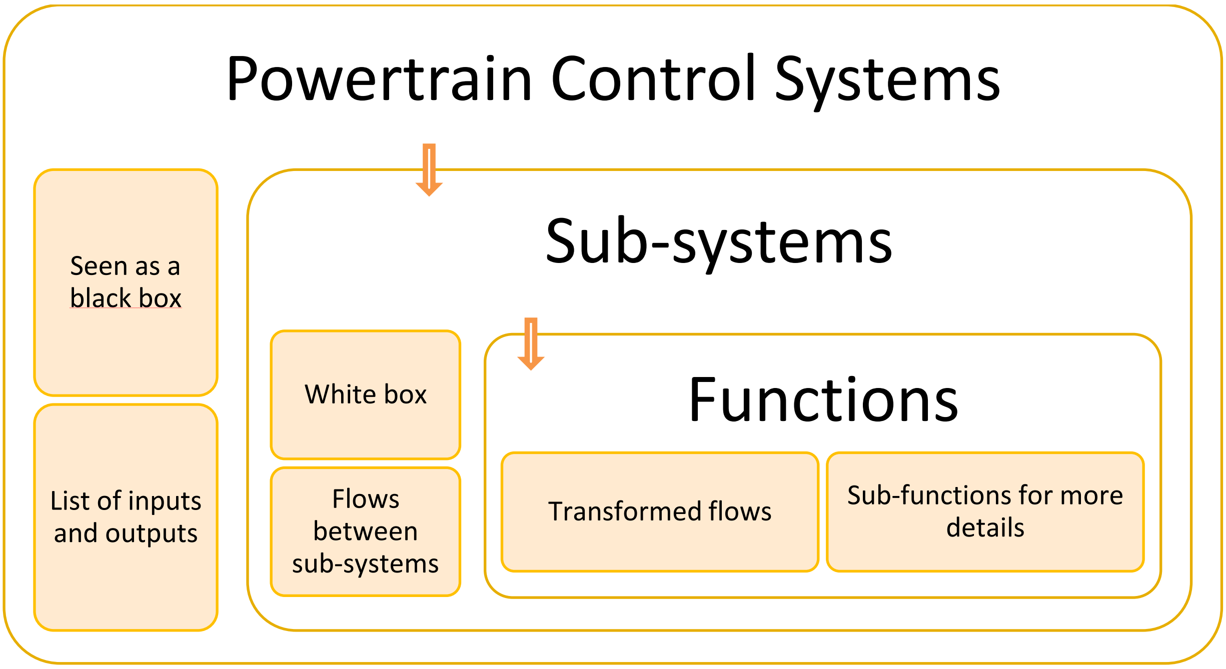

Figure 18: Representation of the functional architecture modeling process

2.2.2. Presentation of Air System

This project has been conducted while working on all five systems but one of them has been the project leader for MagicDraw experimentation: **Air System**. It is for that reason that the modeling of systems architectures of this thesis work will be in majority from this system. The Air System team has the responsibility to establish and control all the air introduction in the cylinders components and strategies. They also have the responsibility of the Exhaust Gas Recirculation (EGR) and the turbocharger when the engine in question is equipped. When a system engineering team is responsible of a perimeter, it is responsible for the components as well. What makes Air System a perfect example for a system leader for modeling experimentation is the high number of components (sensors included).

The FBS of Air System and its decomposition in components (physical breakdown structure or PBS) are in **appendices**. For simplicity, only the decomposition in components for the "EGR" sub-system and its sensors owned by the "Acquisition" sub-system will be shown. "EGR" sub-system will be presented in Chapter 3 by giving its physical architecture.

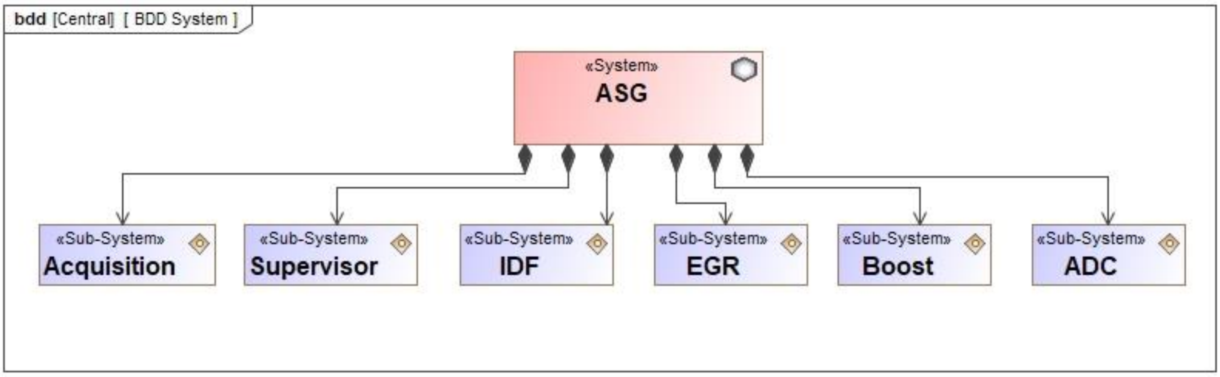

Figure 19: Block Definition Diagram of Air System

2.2.3. Introduction to Inter-Systems Modeling

As indicated previously, one of the main challenges of systems modeling is to keep the coherence between systems and/or sub-systems. Some checks must be put in place to insure this inter-systems coherence. Few means exist to do that, but their use depends on the modeling tool chosen. With MagicDraw, one can generate documents with flows tables, create report with changes from a version to another (excel or word files) and send notifications to other systems (with network collaboration mode) with flows created, deleted or modified. Without these means, the only way to insure a coherence between systems is for the systems architects to communicate and to exchange reports extracted manually. The big advantage of MagicDraw and other tools of architectures modeling is the automated extracts that can be generated quite easily.

The principal topics one pay attention when several systems are implicated concern generally the flows exchanged. The name, the nature and the definition of the flow must be the same for all the systems that use that flow. Secondly, before modeling that a system consumes a flow from another system, one must make sure that this latter system produces that flow. It may seem trivial, but the correctness and coherence of the modeling depends mostly on it. If one changes the view, the same information has to be found with the exact name.

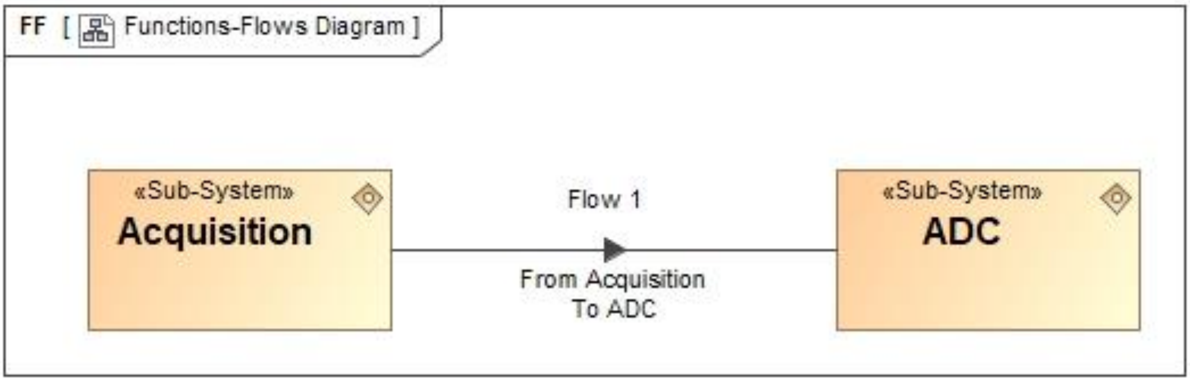

Figure 20: Flow 1 is sent from Acquisition sub-system to ADC sub-system

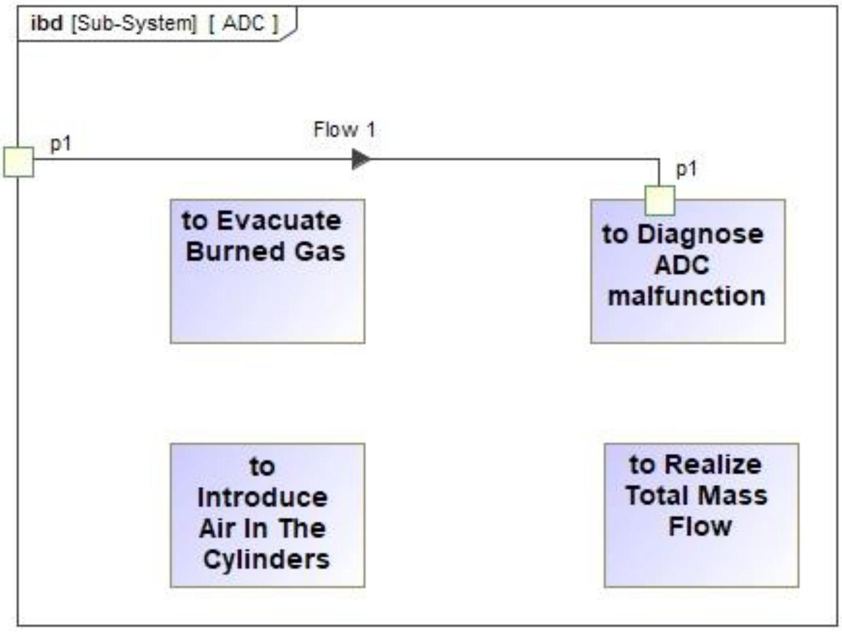

Figure 21: The same Flow 1 is found inside the ADC box

The previous figures 20 and 21, show the propagation of a flow inside the ADC sub-system. This is a very simple example of how a flow should propagate inside a “box”. From the model, a table of all the flows exchanged can be generated and shared. Another simple example is given in the next figures 22 and 23. Few flows were created between the two previous boxes and a table summarizing these flows for inter-system check is automatically created.

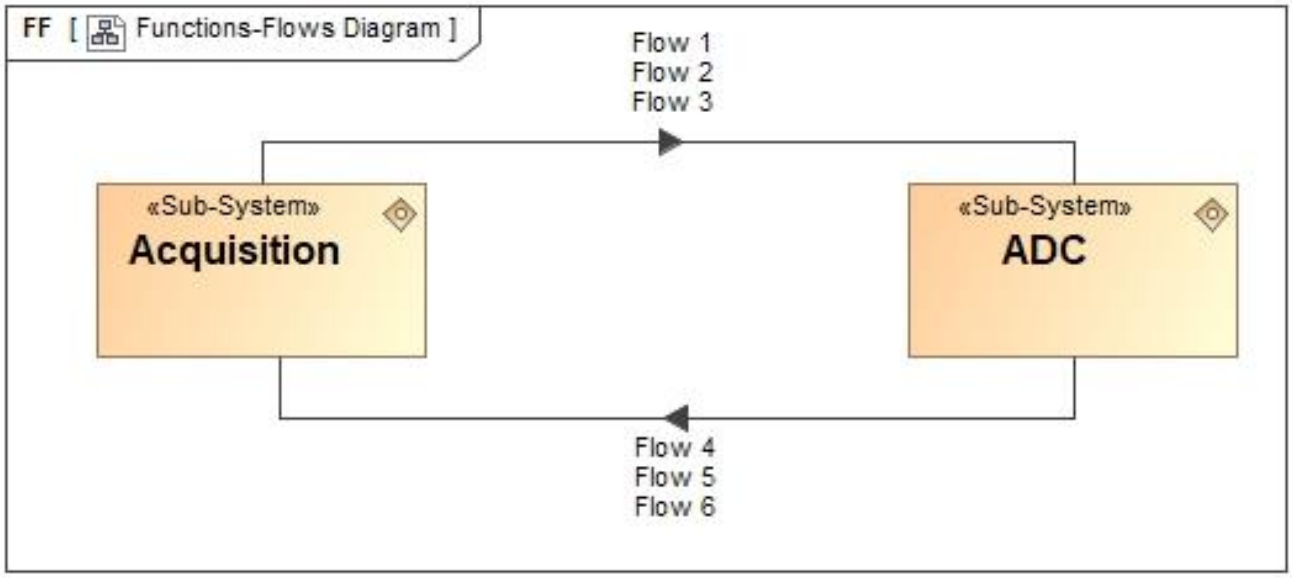

Figure 22: Flows exchanged between Acquisition and ADC sub-systems

#	Name	Information Target	Information Source
1	Flow 1	ADC	Acquisition
2	Flow 2	ADC	Acquisition
3	Flow 3	ADC	Acquisition
4	Flow 4	Acquisition	ADC
5	Flow 5	Acquisition	ADC
6	Flow 6	Acquisition	ADC

Figure 23: Table of exchanged flows between Acquisition and ADC sub-systems

One can also create a sequence diagram highlighting these inter-system exchanges with an added value: the temporality of the exchanges is represented which means it is possible to know which system send what flow to whom and when. An example of sequence diagram is shown in figure 24.

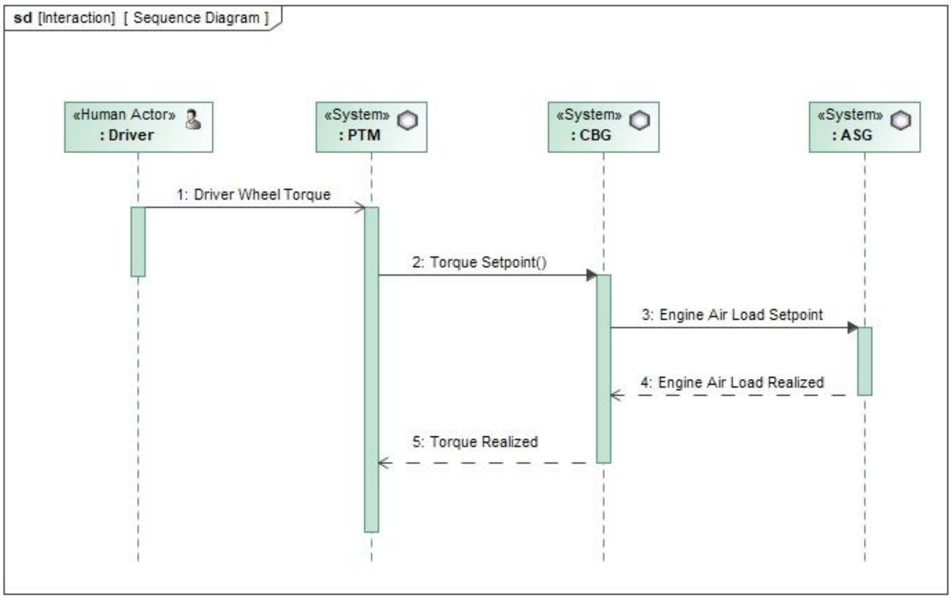

Figure 24: Sequence Diagram representing inter-system exchanges

Summary

To conclude, this thesis work took place in the context of future European Emissions Standards Euro7 within the Systems Engineering Department of Groupe Renault. This objective was to model some architectures of the powertrain control systems. This chapter summarized the organization of these systems in the department and presented the system leader which is Air Path System. Also, the modeling tool used for these six months at Groupe Renault was MagicDraw. A modeling tool based on SysML, a system engineering language which propose several diagrams types for better understanding of a system. We introduced also the inter-system modeling concept which is very important while modeling. Indeed, one must pay attention to these exchanged flows for keeping a coherence.

Chapter 3 – Results and Interpretation

This chapter will present few architectures from Air Path System modeled during these six months of internship. As indicated in the previous chapter, Air Path System is decomposed in several sub-systems (ADC, Acquisition, Supervisor, Boost and IDF). We propose to focus only on the sub-systems Supervisor and Boost. For confidentiality reasons, the flows names are hidden.

3.1 Systems Architectures of Air System

3.1.1 Functional Diagrams

The architecture that is essential to the systems modeling is the functional architecture or functional diagram. This section presents the functional diagrams of two sub-systems of Air System: "Boost" and "Supervisor". The sub-system "Boost" defines the operations of the turbocharger. It settles all the functions that allow the gas to be compressed and go into the intake manifold. The "Supervisor" sub-system defines all the setpoints for all the sub-systems based on information coming from the sensors ("Acquisition" sub-system). See figure 25 for a global presentation of Air Path Supervisor sub-system.

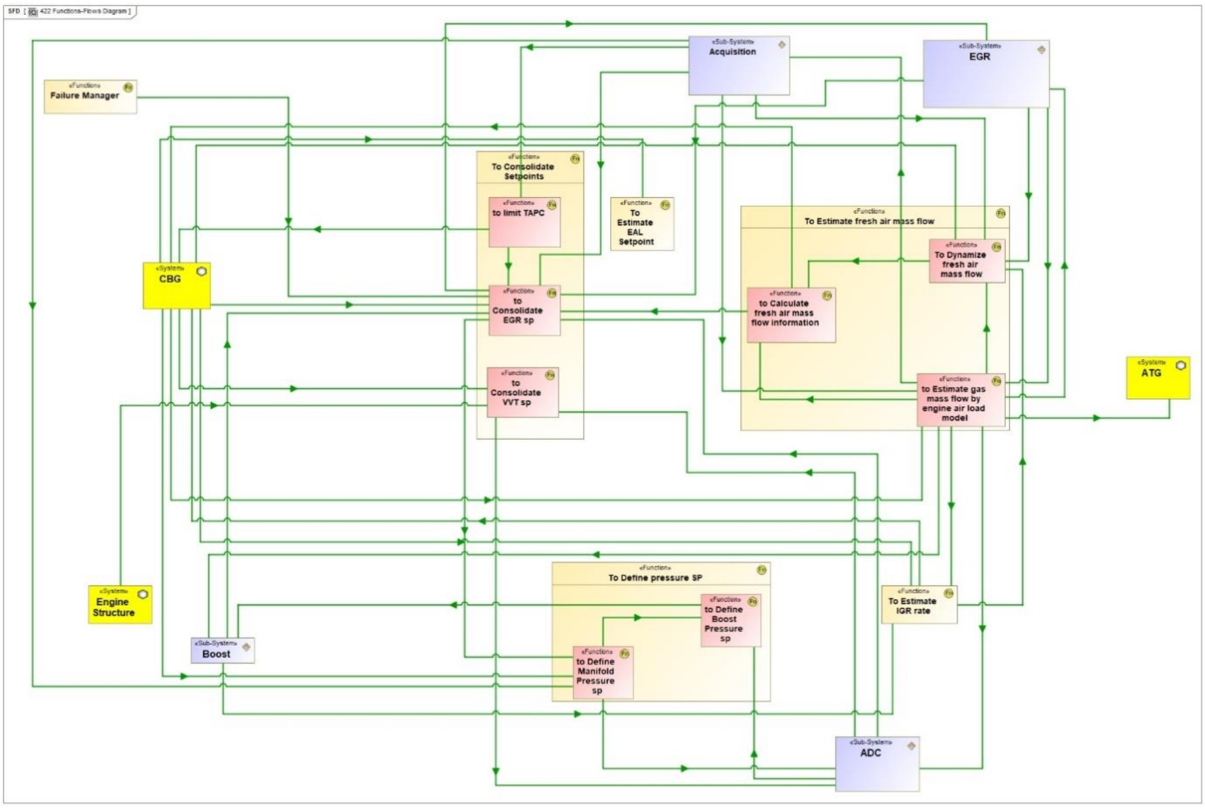

Figure 25: Functional architecture of "Supervisor" Sub-system

As one can see, the architectures are not easily read. That proves the complexity of our systems nowadays.

Some rules had to be voted internally so the architecture can be understood by other departments. The color of the flows specifies the type of this latter. A green arrow means that the flow is a flow of **data**. In the next figure, few arrows will have the color black and others will be drawn in red. The black color specifies a flow of **matter** and the red color specifies a flow of **energy**. These three main types of flows must be distinguished for better understanding.

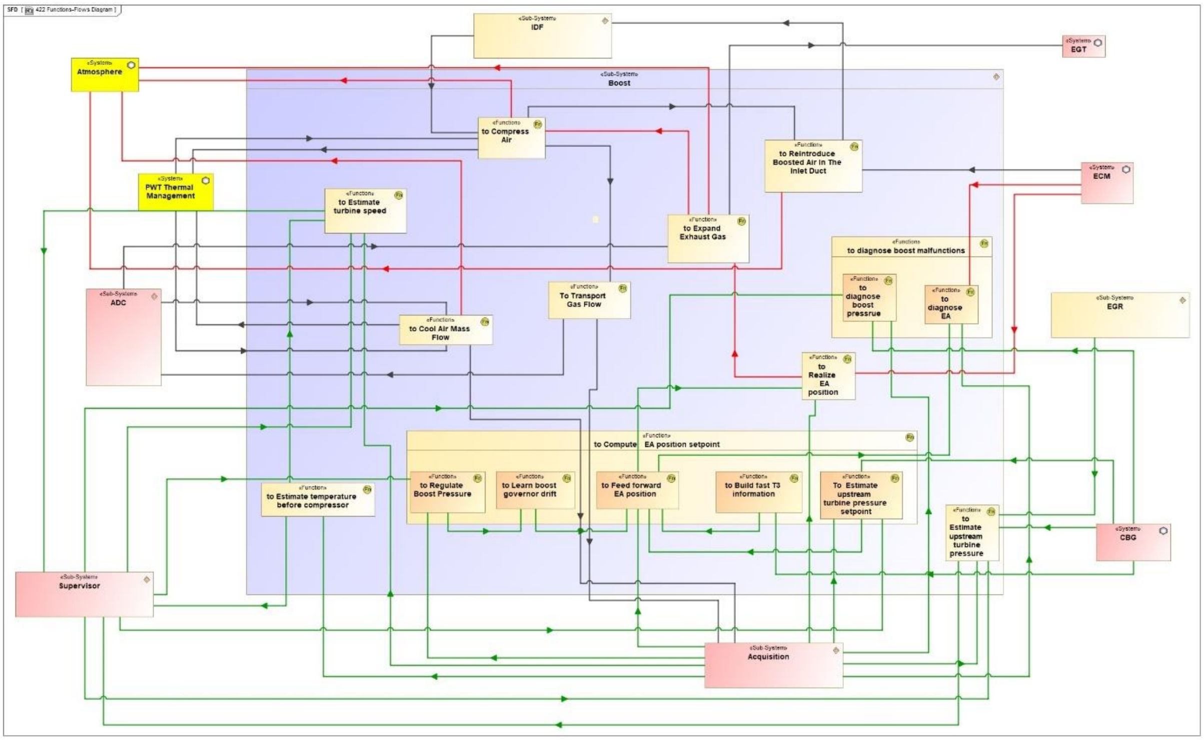

Figure 26: Functional architecture of Boost sub-system

#	Name	Element ID	Role	Role
1		_19_0_1_77101b0_1561981731566_469513_63395	-Acquisition : Acquisition	to Consolidate EGR sp : To Consolidate EGR sp
2		_19_0_1_77101b0_1561981700722_773229_63381	-Acquisition : Acquisition	to limit TAPC : To limit TAPC
3		_19_0_1_77101b0_1561982458597_28092_63758	-Acquisition : Acquisition	to Define Manifold Pressure sp : To Define Manifold Pressure sp
4		_19_0_1_77101b0_1561982573552_501022_63842	-Acquisition : Acquisition	To Dynamize fresh air mass flow : To Dynamize fresh air mass flow
5		_19_0_1_77101b0_1561982555419_943528_63828	-Acquisition : Acquisition	to Estimate gas mass flow by engine air load model : To Estimate gas mas...
6		_19_0_1_77101b0_1561981866902_640714_63451	-ADC : ADC	to Consolidate EGR sp : To Consolidate EGR sp
7		_19_0_1_77101b0_1561982040552_152566_63542	-ADC : ADC	to Consolidate VVT sp : To Consolidate VVT sp
8		_19_0_1_77101b0_1561982117649_930863_63584	-ADC : ADC	to Define Boost Pressure sp : To Define Boost Pressure sp
9		_19_0_1_77101b0_1561982396259_478143_63730	-Boost : Boost	-To Estimate IGR rate : To Estimate IGR rate
10		_19_0_1_77101b0_1561981932770_114413_63493	-Boost : Boost	to Consolidate EGR sp : To Consolidate EGR sp
11		_19_0_1_77101b0_1561982191576_814146_63626	+CBG : CBG	-To Estimate EAL Setpoint : To estimate EAL sp
12		_19_0_1_77101b0_1561982328450_445192_63702	+CBG : CBG	-To Estimate IGR rate : To Estimate IGR rate
13		_19_0_1_77101b0_1561981919084_518617_63479	+CBG : CBG	to Consolidate EGR sp : To Consolidate EGR sp
14		_19_0_1_77101b0_1561982005629_64868_63514	+CBG : CBG	to Consolidate VVT sp : To Consolidate VVT sp
15		_19_0_1_77101b0_1561982164686_526689_63612	+CBG : CBG	to Define Manifold Pressure sp : To Define Manifold Pressure sp
16		_19_0_1_77101b0_1561982238579_833131_63658	+CBG : CBG	To Dynamize fresh air mass flow : To Dynamize fresh air mass flow
17		_19_0_1_77101b0_1561982275478_663731_63674	+CBG : CBG	to Estimate gas mass flow by engine air load model : To Estimate gas mas...
18		_19_0_1_77101b0_1561981804075_783091_63423	-EGR : EGR	to Consolidate EGR sp : To Consolidate EGR sp
19		_19_0_1_77101b0_1561982589261_264310_63856	-EGR : EGR	To Dynamize fresh air mass flow : To Dynamize fresh air mass flow
20		_19_0_1_77101b0_1561982621915_277224_63884	-EGR : EGR	to Estimate gas mass flow by engine air load model : To Estimate gas mas...
21		_19_0_1_77101b0_1561982022317_575308_63528	-Engine Structure : Engine Structure	to Consolidate VVT sp : To Consolidate VVT sp
22		_19_0_1_77101b0_1561981485546_125162_63339	-Failure Manager : Failure Manager	to Consolidate EGR sp : To Consolidate EGR sp
23		_19_0_1_77101b0_1561982303433_468670_63688	-To Estimate IGR rate : To Estimate IGR rate	+CBG : CBG
24		_19_0_1_77101b0_1561982606919_595768_63870	-To Estimate IGR rate : To Estimate IGR rate	To Dynamize fresh air mass flow : To Dynamize fresh air mass flow
25		_19_0_1_77101b0_1561981780158_115874_63409	to Consolidate EGR sp : To Consolidate EGR sp	-EGR : EGR
26		_19_0_1_77101b0_1561981902932_977885_63465	to Consolidate EGR sp : To Consolidate EGR sp	to Define Manifold Pressure sp : To Define Manifold Pressure sp
27		_19_0_1_77101b0_1561982061736_565430_63556	to Consolidate VVT sp : To Consolidate VVT sp	-ADC : ADC
28		_19_0_1_77101b0_1561981572691_397834_63353	to limit TAPC : To limit TAPC	+CBG : CBG
29		_19_0_1_77101b0_1561982422639_196579_63744	to Define Boost Pressure sp : To Define Boost Pressure...	-Boost : Boost
30		_19_0_1_77101b0_1561982145488_561077_63598	to Define Manifold Pressure sp : To Define Manifold Pr...	-ADC : ADC
31		_19_0_1_77101b0_1561982215002_389906_63644	to Calculate fresh air mass flow information : To Calcu...	+CBG : CBG
32		_19_0_1_77101b0_1561981846132_638095_63437	to Calculate fresh air mass flow information : To Calcu...	to Consolidate EGR sp : To Consolidate EGR sp
33		_19_0_1_77101b0_1561982517150_162823_63800	to Estimate gas mass flow by engine air load model : ...	-Acquisition : Acquisition
34		_19_0_1_77101b0_1561982688432_927062_63940	to Estimate gas mass flow by engine air load model : ...	-ADC : ADC
35		_19_0_1_77101b0_1561982653237_587329_63912	to Estimate gas mass flow by engine air load model : ...	-ATG : ATG
36		_19_0_1_77101b0_1561982367255_436905_63716	to Estimate gas mass flow by engine air load model : ...	-Boost : Boost
37		_19_0_1_77101b0_1561982637448_842511_63898	to Estimate gas mass flow by engine air load model : ...	-EGR : EGR
38		_19_0_1_77101b0_1561982669526_815160_63926	to Estimate gas mass flow by engine air load model : ...	-To Estimate IGR rate : To Estimate IGR rate

Figure 27: Table of all the flows exchanged between functions in the Supervisor Sub-system

#	Name	Element ID	△ Role	Role
1		_19_0_1_77101b0_1561992548279_990059_65212	-Acquisition : Acquisition	To Estimate upstream turbine pressure setpoint : ...
2		_19_0_1_77101b0_1561992431765_943252_65170	-Acquisition : Acquisition	to Feed forward EA position : To Feed forward E...
3		_19_0_1_77101b0_1561992203279_360999_65128	-Acquisition : Acquisition	to Regulate Boost Pressure : To Regulate Boost Pre...
4		_19_0_1_77101b0_1561992578215_560013_65226	-Acquisition : Acquisition	to diagnose boost pressrue : To diagnose boost pre...
5		_19_0_1_77101b0_1561992651621_598586_65254	-Acquisition : Acquisition	to diagnose EA : To diagnose EA
6		_19_0_1_77101b0_1561992395726_950435_65156	-Acquisition : Acquisition	to Estimate temperature before compressor : To Es...
7		_19_0_1_77101b0_1561991921853_59688_64998	-Acquisition : Acquisition	to Estimate turbine speed : To Estimate turbine speed
8		_19_0_1_77101b0_1561992614928_886924_65240	-Acquisition : Acquisition	to Estimate upstream turbine pressure : To Estimat...
9		_19_0_1_77101b0_1561992751172_848597_65296	-Acquisition : Acquisition	to Realize EA position : To Realize EA position
10		_19_0_1_77101b0_1561992026000_107526_65040	-ADC : ADC	to Cool Air Mass Flow : To Cool Air Mass Flow
11		_19_0_1_77101b0_1561991551308_800115_64914	-ADC : ADC	to Expand Exhaust Gas : To Expand Exhaust Gas
12		_19_0_1_77101b0_1561992523171_194172_65198	-CBG : CBG	to Build fast T3 information : To Build fast T3 infor...
13		_19_0_1_77101b0_1561992708171_307814_65282	-CBG : CBG	To Estimate upstream turbine pressure setpoint : ...
14		_19_0_1_77101b0_1561991416963_32664_64872	-CBG : CBG	to diagnose boost pressrue : To diagnose boost pre...
15		_19_0_1_77101b0_1561992682664_178946_65268	-CBG : CBG	to Estimate upstream turbine pressure : To Estimat...
16		_19_0_1_77101b0_1561993118094_236829_65426	-ECM : ECM	to diagnose EA : To diagnose EA
17		_19_0_1_77101b0_1561993151411_866369_65440	-ECM : ECM	to Realize EA position : To Realize EA position
18		_19_0_1_77101b0_1561991348862_494258_64844	-ECM : ECM	to Reintroduce Boosted Air In The Inlet Duct : To R...
19		_19_0_1_77101b0_1561993177783_518957_65454	-EGR : EGR	to Estimate upstream turbine pressure : To Estimat...
20		_19_0_1_77101b0_1561990953246_500419_64716	-IDF : IDF	to Compress Air : To Compress Air
21		_19_0_1_77101b0_1561991269098_602886_64802	-PWT Thermal Management : PWT Thermal Management	to Compress Air : To Compress Air
22		_19_0_1_77101b0_1561991974150_549675_65012	-PWT Thermal Management : PWT Thermal Management	to Cool Air Mass Flow : To Cool Air Mass Flow
23		_19_0_1_77101b0_1561992816191_89828_65324	-Supervisor : Supervisor	To Estimate upstream turbine pressure setpoint : ...
24		_19_0_1_77101b0_1561991608626_819227_64942	-Supervisor : Supervisor	to Regulate Boost Pressure : To Regulate Boost Pre...
25		_19_0_1_77101b0_1561991577294_15792_64928	-Supervisor : Supervisor	to diagnose boost pressrue : To diagnose boost pre...
26		_19_0_1_77101b0_1561991651273_402165_64956	-Supervisor : Supervisor	to Estimate turbine speed : To Estimate turbine speed
27		_19_0_1_77101b0_1561992788802_497914_65310	-Supervisor : Supervisor	to Estimate upstream turbine pressure : To Estimat...
28		_19_0_1_77101b0_1561991051135_854588_64760	to Compress Air : To Compress Air	-Atmosphere : Atmosphere
29		_19_0_1_77101b0_1561991291929_840887_64816	to Compress Air : To Compress Air	-PWT Thermal Management : PWT Thermal Manag...
30		_19_0_1_77101b0_1561992927610_50525_65352	to Cool Air Mass Flow : To Cool Air Mass Flow	-Acquisition : Acquisition
31		_19_0_1_77101b0_1561992069483_879017_65072	to Cool Air Mass Flow : To Cool Air Mass Flow	-Atmosphere : Atmosphere
32		_19_0_1_77101b0_1561991995226_579198_65026	to Cool Air Mass Flow : To Cool Air Mass Flow	-PWT Thermal Management : PWT Thermal Manag...
33		_19_0_1_77101b0_1561992371639_949008_65142	to Estimate temperature before compressor : To Estima...	-Supervisor : Supervisor
34		_19_0_1_77101b0_1561991687797_962946_64970	to Estimate turbine speed : To Estimate turbine speed	-Supervisor : Supervisor
35		_19_0_1_77101b0_1561992846107_679134_65338	to Estimate upstream turbine pressure : To Estimate up...	-Supervisor : Supervisor
36		_19_0_1_77101b0_1561990993368_620227_64744	to Expand Exhaust Gas : To Expand Exhaust Gas	-Atmosphere : Atmosphere
37		_19_0_1_77101b0_1561991484172_356833_64886	to Expand Exhaust Gas : To Expand Exhaust Gas	-EGT : EGT
38		_19_0_1_77101b0_1561991371912_303415_64858	to Reintroduce Boosted Air In The Inlet Duct : To Reintro...	-Atmosphere : Atmosphere
39		_19_0_1_77101b0_1561990973478_16709_64730	to Reintroduce Boosted Air In The Inlet Duct : To Reintro...	-IDF : IDF
40		_19_0_1_77101b0_1561993071067_720147_65412	To Transport Gas Flow : To Transport Gas Flow	-Acquisition : Acquisition
41		_19_0_1_77101b0_1561992045395_54187_65054	To Transport Gas Flow : To Transport Gas Flow	-ADC : ADC

Figure 28: Table of all the flows exchanged between functions in the Boost Sub-system

Therefore, one can easily say that the complexity of the system is reflected on the architecture. Indeed, the more flows a system exchanges with others, the more difficult the reading of this architecture become. The tables shown on figures 27 and 28 are always generated with the architecture for different reasons, one of them is the verification of the diagram. It is another view of the system.

3.1.2 Physical Diagrams

Physical architectures bring more comprehension to the system thanks to their concrete modeling. It is a great communication way that illustrates one or a group of components and the physical flows that are exchanged. Besides, it is very useful to draw a physical architecture for a representation of the all engine and the location of all components and sensors. The following physical architecture is a representation of the EGR sub-system of Air Path System. It represents all the sub-components and the flows that go through each component.

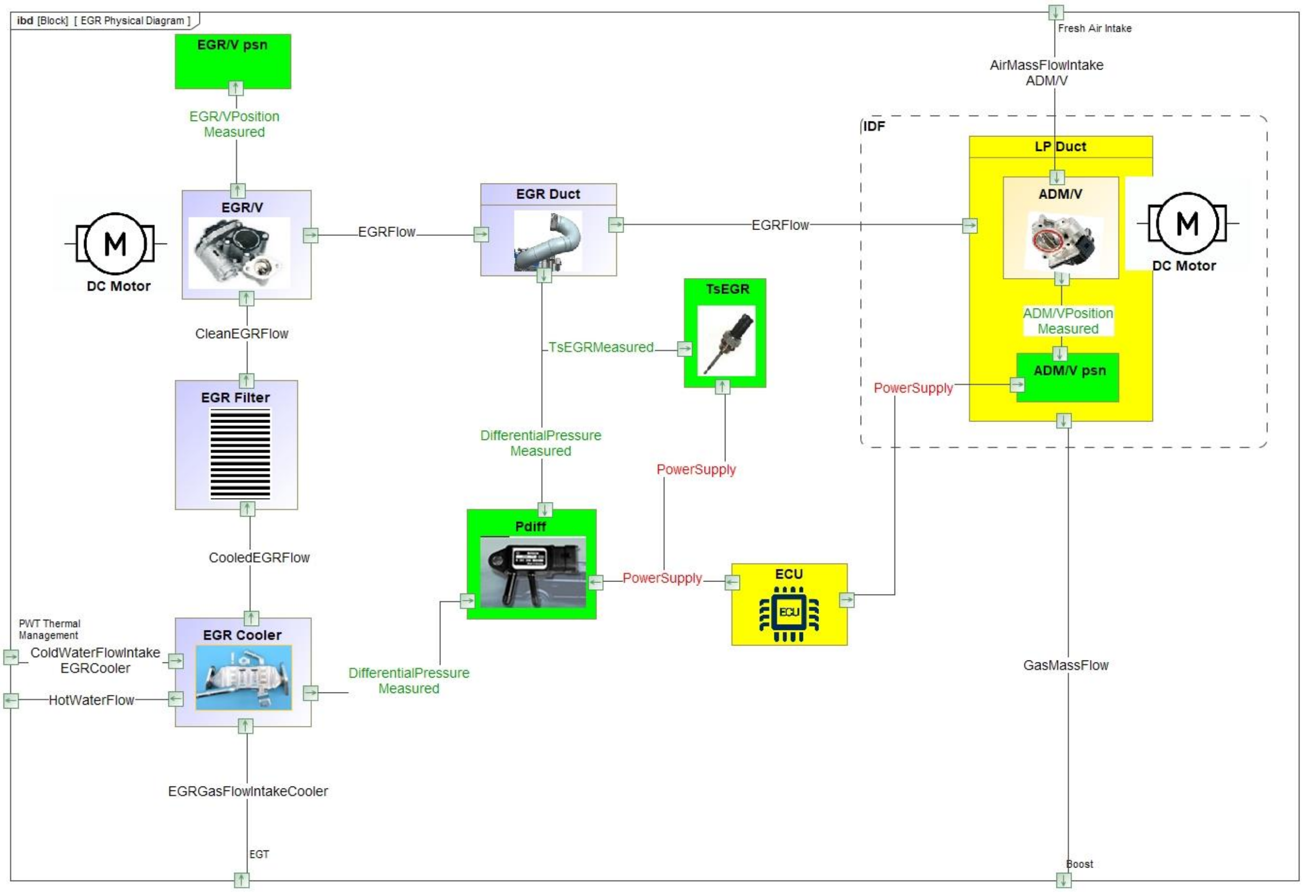

Figure 29: Physical architecture of the EGR sub-system

The same rules for colors use are applied here:

- Green: flow of data
- Black: flow of matter
- Red: flow of energy

One can create the same documents as created for the functional architecture. It can be important to draw a list of all physical flows for the same reasons as indicated before, see figure 30.

#	Name	Element ID	Role	Role
1	AirMassFlowIntakeADM/V	_19_0_1_77101b0_1558598106286_38573_62215	in Fresh Air Intake : Intake ADM/V	in intake ADM/V : Intake ADM/V
2	CleanEGRFlow	_19_0_1_77101b0_1558690499264_694330_64124	out intake EGR/V : ~Intake EGR/V	in intake EGR/V : Intake EGR/V
3	ColdWaterFlowIntakeEGRCooler	_19_0_1_77101b0_1558699749504_934435_64395	in PWT Thermal Management : PWT Thermal Manage...	in PWT Thermal Management : PWT Thermal Manage...
4	CooledEGRFlow	_19_0_1_77101b0_1558690496761_139175_64109	out intake EGR Filter : ~Intake EGR Filter	in intake EGR Filter : Intake EGR Filter
5	DifferentialPressureMeasured	_19_0_1_77101b0_1558690091509_451209_63861	out ECU : ~ECU	in ECU1 : ECU
6	DifferentialPressureMeasured	_19_0_1_77101b0_1558690185235_906640_63908	out ECU : ~ECU	in ECU2 : ECU
7	EGR/VPositionMeasured	_19_0_1_77101b0_1558698342600_152034_64267	out ECU : ~ECU	in ECU : ECU
8	EGRFlow	_19_0_1_77101b0_1558690371613_93692_64009	out EGR Duct / LP Duct : ~EGR Duct / LP Duct	in EGR/V / LP Duct : EGR Duct / LP Duct
9	EGRFlow	_19_0_1_77101b0_1558690344143_593118_63975	out EGR/V / LP Duct : ~EGR/V / EGR Duct	in EGR/V / EGR Duct : EGR/V / EGR Duct
10	EGRGasFlowIntakeCooler	_19_0_1_77101b0_1558690520880_555020_64156	in intake EGR Cooler : Intake EGR Cooler	in intake EGR Cooler : Intake EGR Cooler
11	GasMassFlow	_19_0_1_77101b0_1558598173314_472641_62337	out boost : ~Boost	out Boost : ~Boost
12	HotWaterFlow	_19_0_1_77101b0_1558699786191_557084_64441	out PWT Thermal Management1 : ~PWT Thermal Mana...	out : ~PWT Thermal Management
13	PowerSupply	_19_0_1_77101b0_1558599772718_426262_62480	out ECU : ~ECU	in ECU : ECU
14	PowerSupply	_19_0_1_77101b0_1558599741947_451903_62458	out ECU : ~ECU	in ECU : ECU
15	PowerSupply	_19_0_1_77101b0_1558597110896_39897_62149	out ECU1 : ~ECU	in : ECU
16	TsEGRMeasured	_19_0_1_77101b0_1558690161124_641995_63893	out ECU : ~ECU	in ECU1 : ECU

Figure 30: Table of physical flows exchanged in EGR sub-system

If we must make an interpretation of the physical architecture and its comparison with the functional architecture, we must say that the physical diagrams are much clearer to read because of the low number of flows between components. Indeed, one needs to represent only the flows of matter between components, the flows of data received by sensors and the flows of energy that power the actuators.

Usually, the components of a system are the physical objects that realize a function or a group of functions. It could be interesting to put in a table the allocation of each components with the functions they realize. For example, the "Air Filter" will realize the function "To filter air". MagicDraw has this functionality that allow us to create such table very easily and so generate a file with every allocation. The following figure 31 illustrates this point for the EGR sub-system.

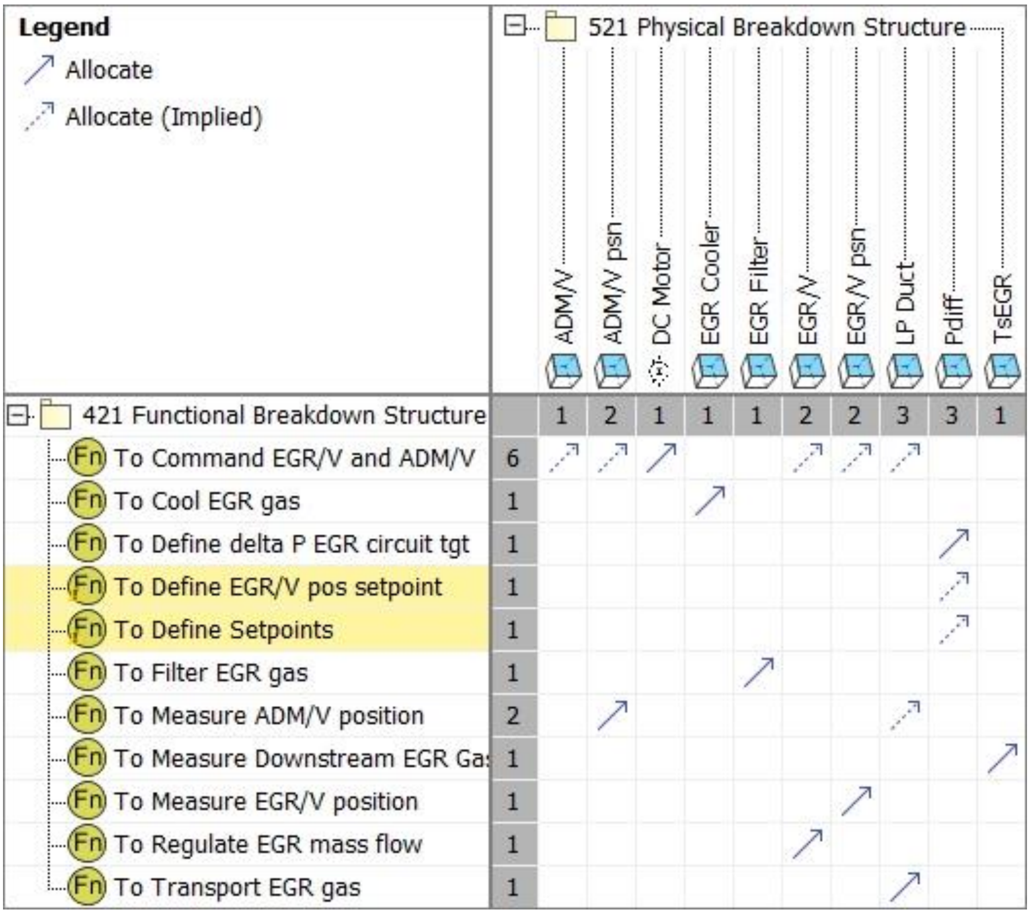

Figure 31: Allocation Table Components/Functions for the EGR sub-system

There are two types of arrows:

- One for the allocation
- One for the implied allocation (dotted arrow)

The implied allocation represents an indirect allocation when a component is linked to another in the physical diagram. Such links are represented in this table.

3.1.3 Requirements Tables

The first chapter of this thesis work settles the basis of Systems Engineering. This domain begins by the reception of requirements coming from different stakeholders. Once the requirements received, the system engineer’s work begins. The requirements must be declined into system technical requirements (STR) then applied to the different components (STRComp). In parallel to that, the requirement is declined in system design document (SDD). Renault and Nissan have their own way to manage requirements. All these breakdown must be presented in front of experts from Renault and Nissan in a review called “System Control Design Review” (SCDR). [9]

The following image represents the process of the SCDR at Renault and Nissan. One can see that the system team begins the process by submitting the first versions of STR and SDD until these latter are frozen with the support of the software team.

Figure 32: Renault Nissan SCDR process

For the modeling, the requirements can be represented in tables and diagrams in order to show the declension from the stakeholder requirement, which is the input, to the STR and SDD which are applied to the functions and components. From these, one can proceeds to impact analysis, which is indicated in the next section. For Air Path System, few requirements modeling were made, and documents generated. The next figures 33 and 34 show the output of such modeling. Again, for confidentiality reasons, the numeric values of these requirements are not given.

#	Name	Text	Traced To	Refined By	Allocated To	Derived From
1	Req_1	Dilution by internal residual gaz : up to x% IGRrate = f(N/EAL) depending on combustion stability	Fuel Economy PWT R			
2	Req_1_1	VVT system shall be able to provide camshaft phasing according to combustion MAP and insure VVT position accuracy of x CA				Req_1
3	Req_1_1_1	VVT system shall be able to provide max amplitude of x°		To move camshaft	VVT	Req_1_1
4	Req_1_1_2	VVT system shall be able to Realize VVT setpoints		To control EV	Solenoid Valve	Req_1_1
5	Req_1_1_3	VVT system shall be able to learn VVT position		To learn VVT positior	SW	Req_1_1
6	Req_1_1_4	VVT system shall be able to regulate VVT position		To regulate VVT posi	SW	Req_1_1

Figure 33: Requirements table for VVT component

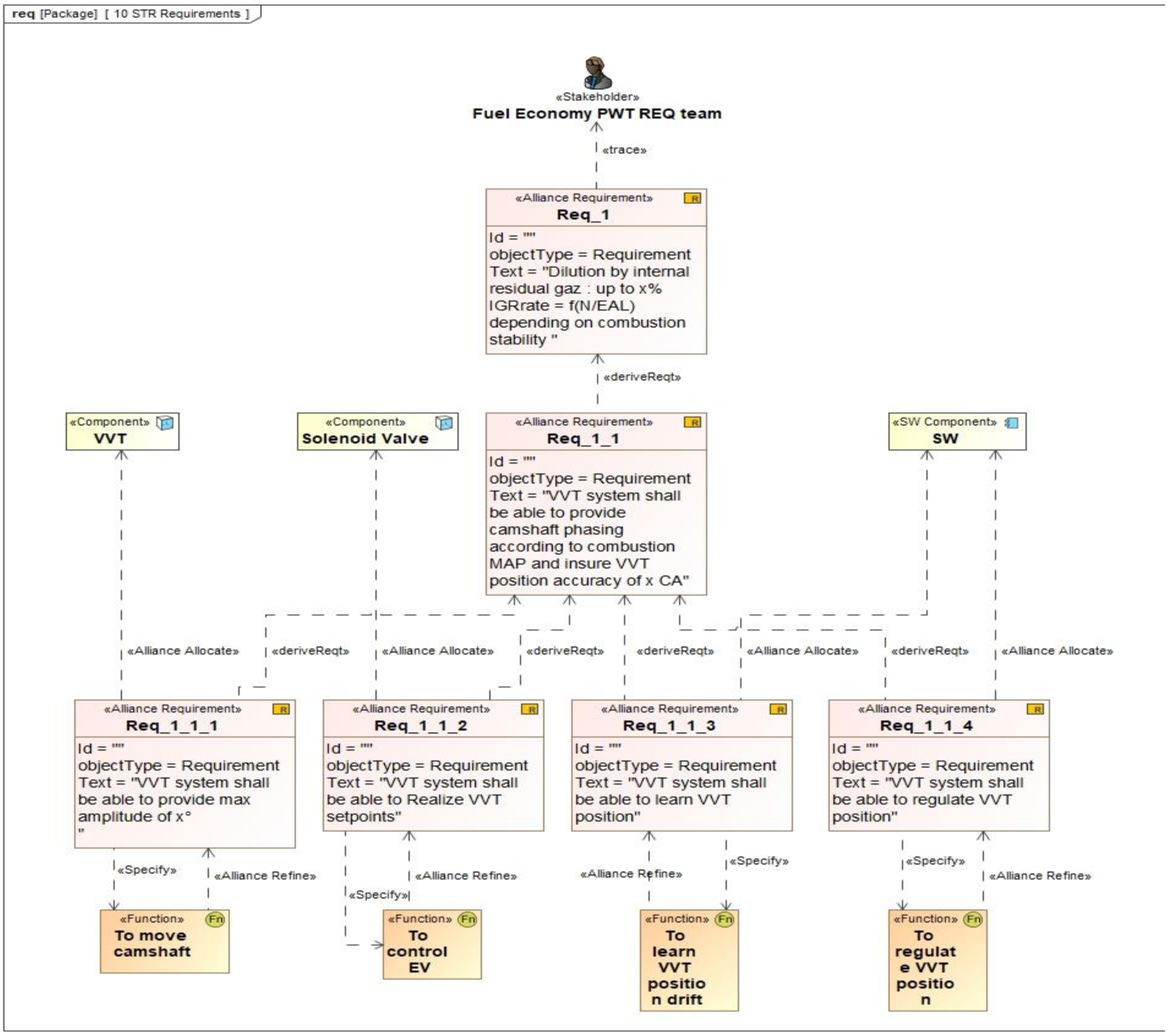

Figure 34: Requirements diagram for VVT component

3.2 Architectures Analysis

3.2.1 Impact Analysis

The big advantage of MagicDraw, and other modeling tool that works like MagicDraw, is the analysis opportunity. The system engineer can verify and analyze the model and observe the propagation of the different flows between elements. The impact analysis is very useful when one wants to predict the impact on the changes of an element. For example, if a function has a different input one can see directly which functions or systems can be impacted. Another example more concrete, if a component has a default, which means doesn't deliver the proper information (for the case of a sensor) or produces a non-correct flow of matter, the other component impacted can be highlighted.

It exists several ways to make an impact analysis with different tools at our disposal. MagicDraw proposes a traceability of all the model's elements which allow us to do such studies. For a traceability analysis, one can draw a **traceability tree** that is visually more adapted if one wants to see the propagation of the flows (see figure 35). Another diagram very useful for traceability is the **dependency matrixes**. All the relations can be marked in such diagrams which allows to see all the elements impacted by a change (see figure 36).

Figure 35: Impact analysis of the function "To Define Manifold Pressure sp" from Supervisor sub-system

This propagation analysis can be used also for requirements engineering. One may want to highlight the requirements impacted from a modification of a component of a function. But this is valid the other way around: one may want to represent the components or functions concerned by a requirement change (see figures 37 and 38).

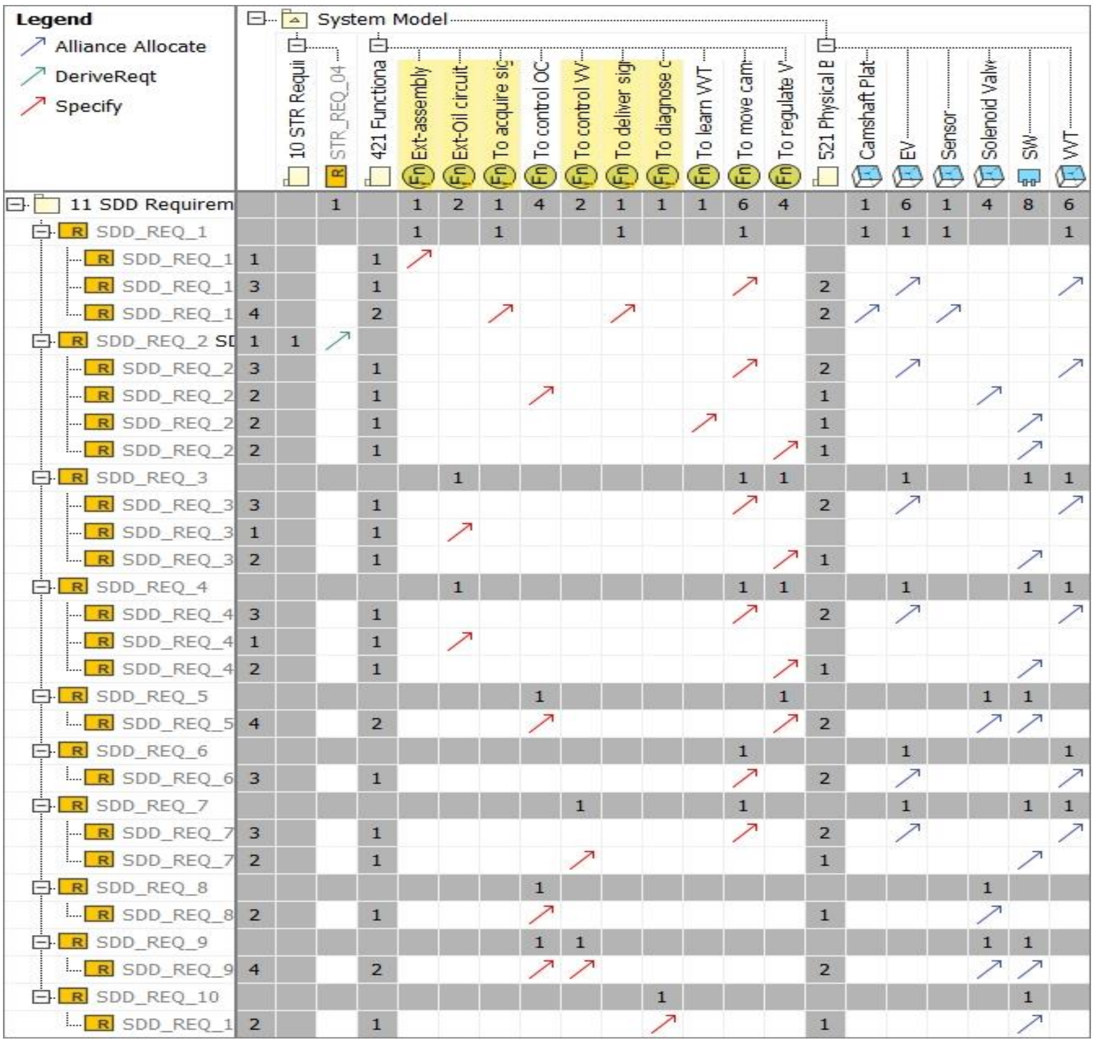

Figure 36: Impact matrix showing the functions and components

For a complete analysis, both documents (matrixes and trees) are needed. That way, one can see both views.

Figure 37: Impact analysis showing the impacts on requirements occurred by the change of a component

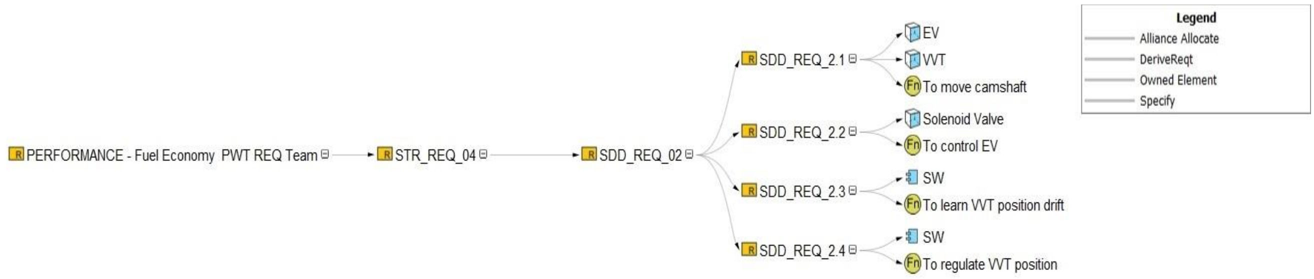

Figure 38: Impact analysis showing the impacts on functions and components occurred by the change of a requirement

The requirements engineering, and the systems engineering are quite different even if these are two close disciplines. However, it is very interesting for the Systems department to have this view of propagation when a requirement changes or is suppressed.

3.2.2 MBSE – MBSA Transition

The last section of this paper deals with the extended work that MBSE (Model-Based System Engineering) can provide to MBSA (Model-Based Safety Assessment). Even if the MBSA is not the subject of this thesis work, the dependability team needs the functional architectures in order to do the FMEA (Failure Modes and Effects Analysis). Basically, the dependability engineer lists all the potential risks that a system can have, the means to detect them, the effects, the causes and the gravity. All these data are grouped in a table. To generate this document, they must know exactly how the system operates and its environment. At Groupe Renault, the dependability team and the system team are part of the same department. This allow a better communication between the teams and a better comprehension of the powertrain control systems.

The principal documents needed by the dysfunctional team are the functional architecture and the physical architecture. These documents regroup the operation of the system and the actuators that realize the different functions. Thus, the system operation and its environment can be described. To be as precise as possible, the system team provide the safety team with dependency matrixes, allocation tables and flows tables. All the documents presented in this paper can be an input to the work of the dependability team.

Summary

To conclude, this chapter presented the results of all the modeling types made during these six months of internship at Groupe Renault. One may keep in mind the principal architectures that are created:

- The functional architecture that details the functional operation of the system
- The physical architecture that describes the physical operation of the system

These two architectures are part of the three views that MBSE propose. The third one being the Operational view has not been part of this work. The architectures that one can find in the operational view are the system life cycle, where all the different phases of life are shown.

Conclusion

In conclusion, this thesis work is the result of six months of internship within the Systems Engineering department of Renault. The main objective of this project was the **modeling of Renault's Powertrain systems architectures**, in development for the Euro 7 emissions standards. The work began by identifying all the elements of the system for their implementation in the model.

To meet this objective, the department received a new modeling tool: MagicDraw. This tool is based on SysML which is a system modeling language very close to UML. It provides several diagrams types that the modeler can use to represent with different viewpoints the system.

The system "powertrain" is divided into five systems (Air System, Combustion system, After-Treatment system, Powertrain Torque Management and Hybrid Management). Even if I had the opportunity to work with all systems, this thesis work focuses only on the Air System which is the most advanced system in term of architectures. The documents generated for this paper were:

- Functional architectures
- Physical architectures
- Sequence diagrams
- Requirements diagrams
- Impact analysis trees
- Dependency matrixes

These results are the output of six months of modeling with MagicDraw. They offer a lot of possibilities to improve the robustness of the model created by the system team and facilitate the work of the dependability team for their safety analysis. Moreover, the documents produced by MagicDraw are used during presentation (design reviews) as communication tools for better understanding.

As future works, one can imagine the implementation of Model-Based Design Simulation directly on the system engineering modeling tool. Indeed, MagicDraw has the functionality of running a simulation of a part or the entire model (using an external plugin). This can speed the development of the product and bring different results to support the creation of new functions.

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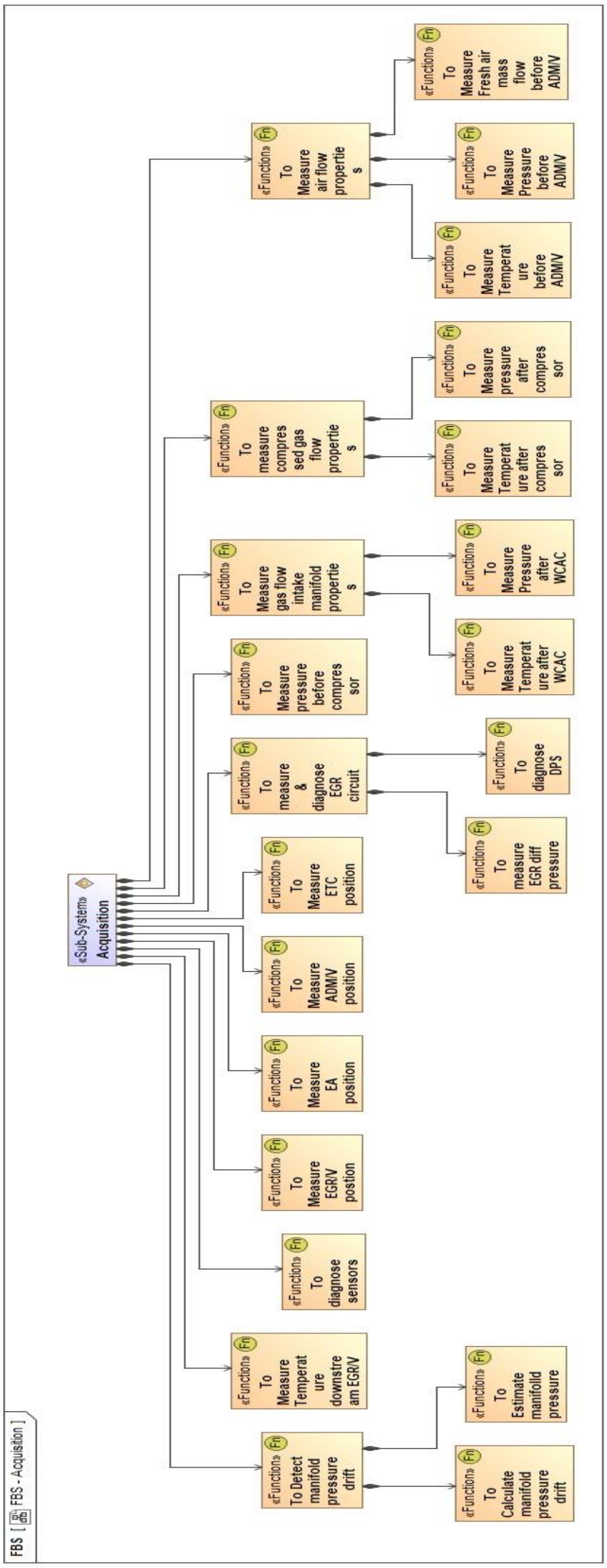
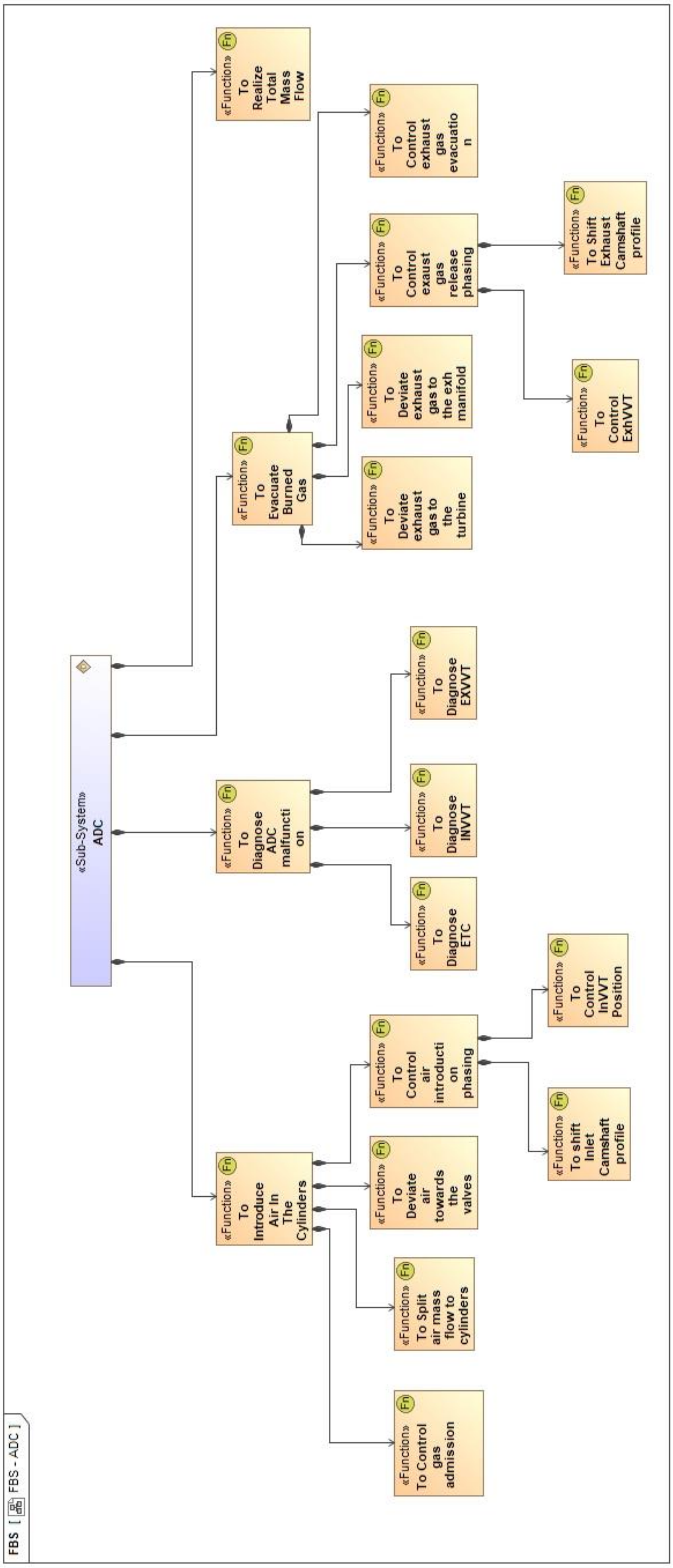
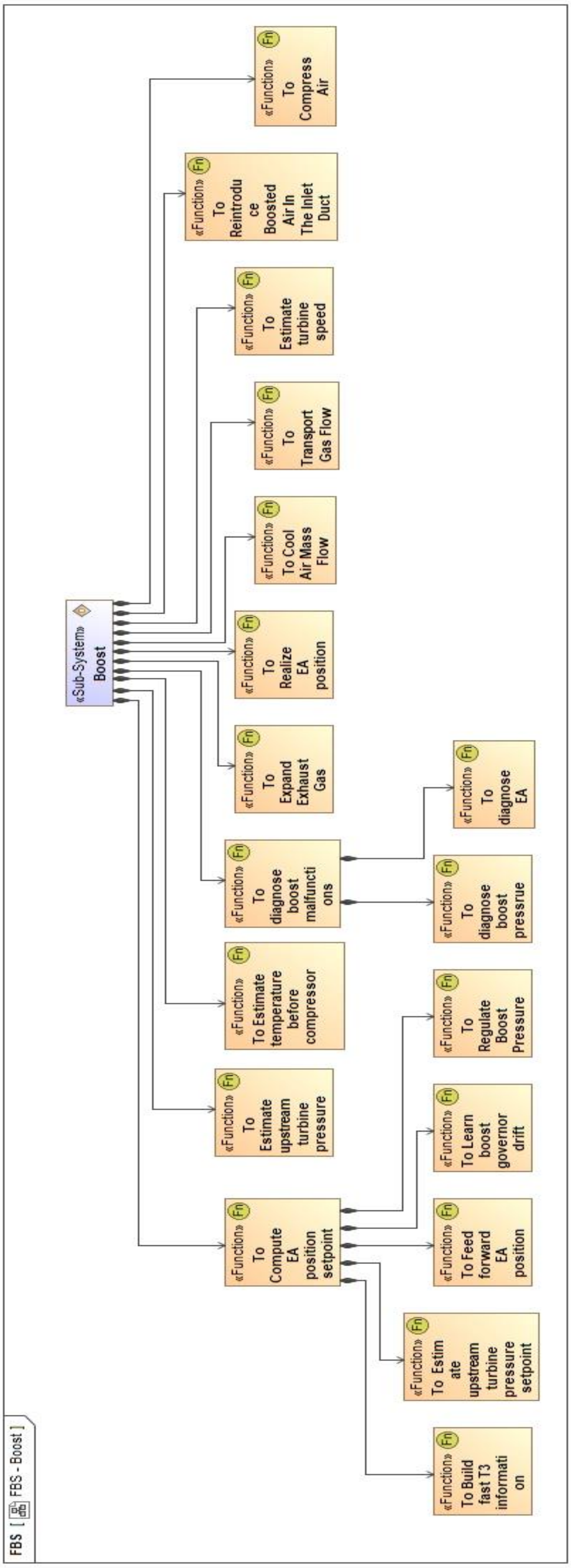
Appendices



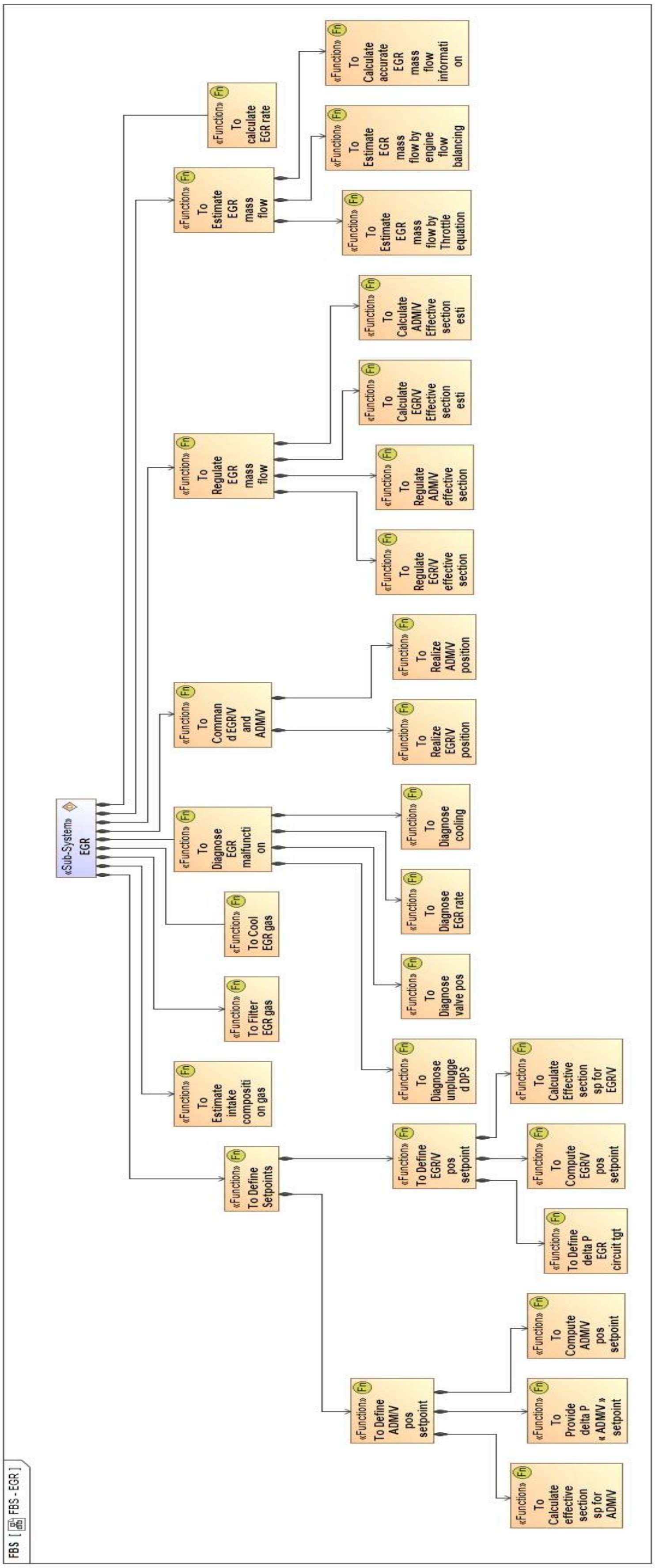
Appendix 1: Functional Breakdown Structure of Acquisition Sub-system



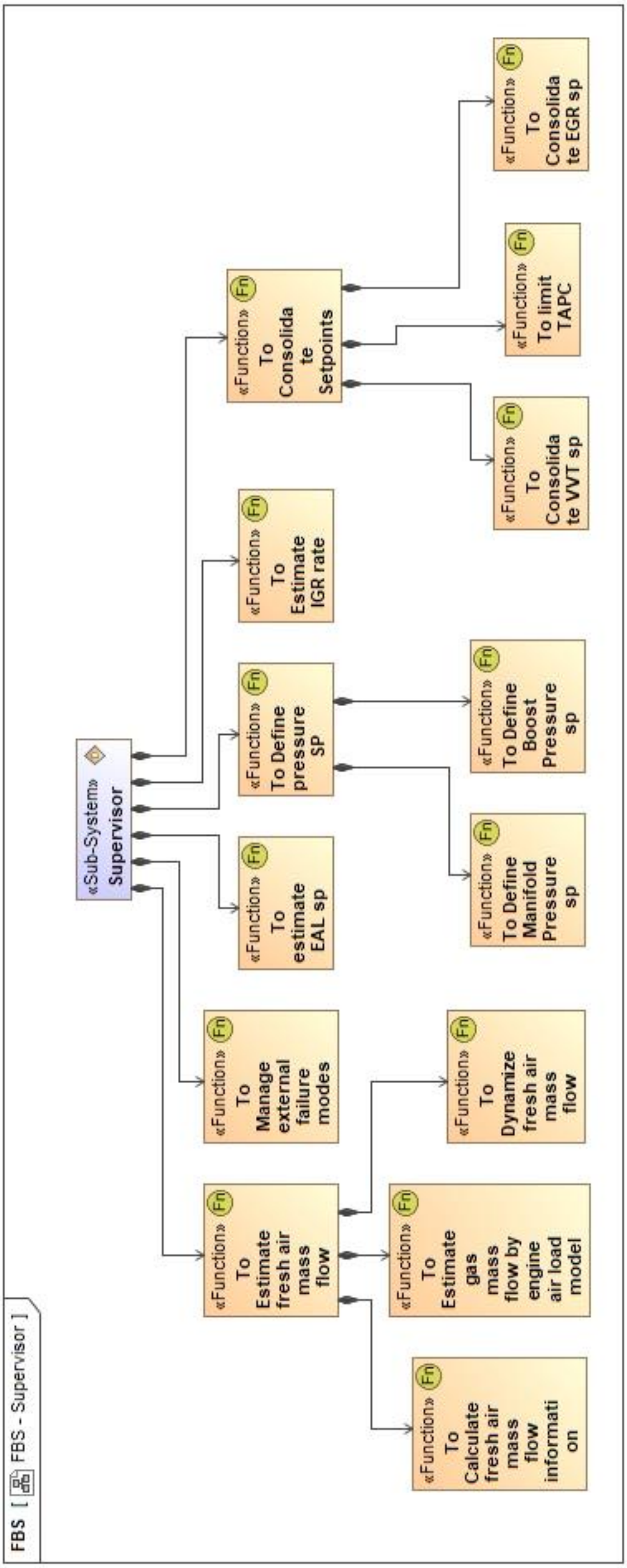
Appendix 2: Functional Breakdown Structure of ADC Sub-system



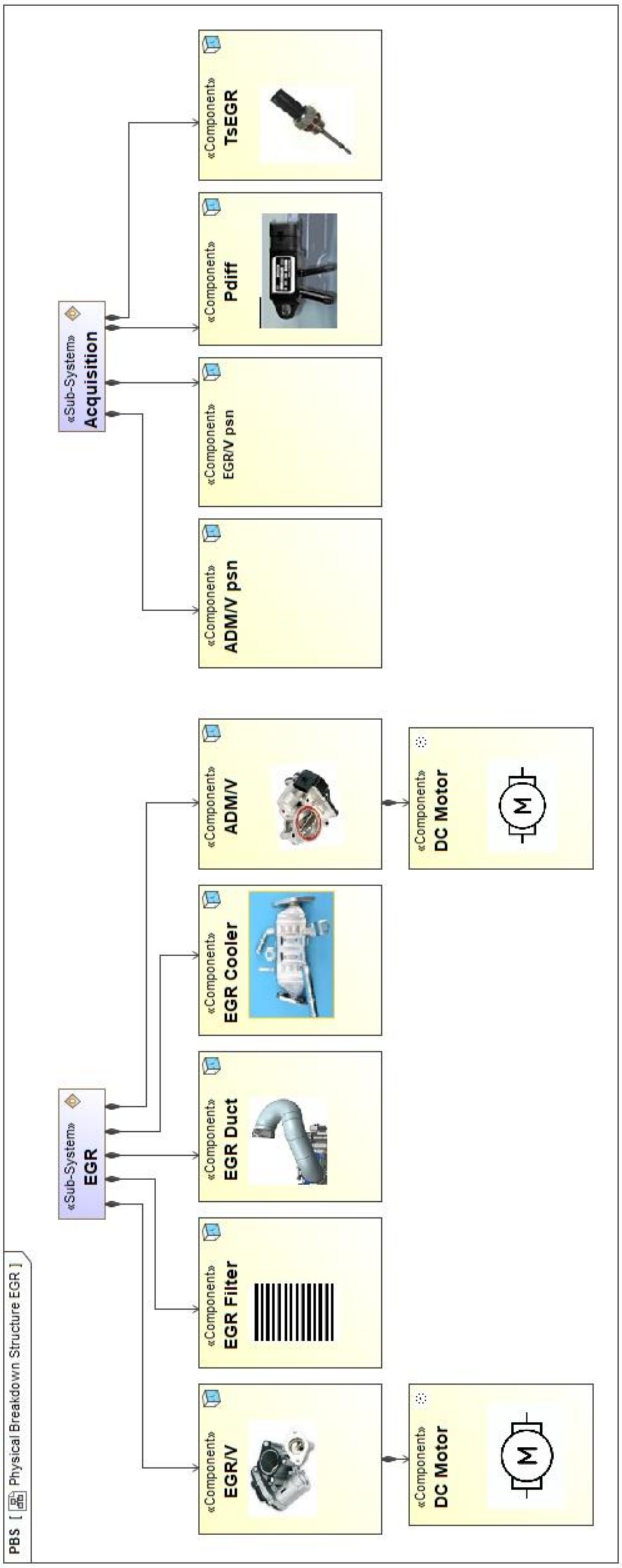
Appendix 3: Functional Breakdown Structure of Boost Sub-system



Appendix 4: Functional Breakdown Structure of EGR Sub-system



Appendix 5: Functional Breakdown Structure of Supervisor Sub-system



Appendix 6: Physical Breakdown Structure of EGR Sub-system and its sensors