



# Object Oriented Failure Modes and Effects Analysis (Climate System)

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Objektorienterad FMEA (klimatsystem)

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# Abstract

*In order to make the product more reliable and efficient, the failures and their occurrence related to the products should be reduced if not eliminated. To achieve that, the approach of Failure Modes Effects Analysis (FMEA) is used in the process development phase where all the aspects of the product failure are generated and studied. With the passage of time the systems began to become more complex and alone FMEA not good enough approach for the complex systems. To handle a complex system is a hard and tedious job which requires more expertise. In complex systems the individual system might have overlaps, their boundaries are often unclear. The computation of information and its transmission between the components is extensive. Object Oriented FMEA resolves these issues by identifying the structure and screening a proper boundary of the system. It looks deeply in to the operational environment and external shared resources. It then decomposes its functions and behaviors in to separable physical, logical and attributes objects. The OO-FMEA approach obeys to the objectives of modern product development process and its principles. This approach makes it comparatively much easier to analyze the complex auto-motive systems that are built in extensive electrical architecture. The systems components perform their task while being interacted, linked or even independent. In this thesis the OO-FMEA approach is implemented on the Climate System of the SPA Hybrid.*

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## **Definitions**

### ***Terms***

#### **Failure**

Failure is defined as the completely loss of envisioned function in any system is called failure.

#### **Failure Mode**

Failure mode is defined as the way failure occurs or the way things fail.

#### **Failure Effects**

The penalties as a result of the Failure are termed as Failure Effects

#### **FMEA**

FMEA is a tool, systematic process for assessment of potential failures modes of any system. It is a systematic process which is used to identify potential failure modes and their potential causes, for the improvement of product reliability

#### **Thermal Management System**

Thermal management as the name shows is the management of heat energy. It is a complicated system in cars which manages the thermal energy in cars.

#### **Simple System**

A system is said to be a simple system when it has limited number of system elements, its boundaries are clear and it has well defined inputs and outputs.

#### **Complex System**

Any system which is composed of various dependent and/or independent, densely interconnected components having multiple level details, with no clear boundaries is said to be a complex system.

#### **Interface**

Interface is when data is transmitted from one entity to another without any feedback between the connected entities. The transfer of data can be one or two ways, but is independent of each other.

#### **Interaction**

Interaction is a type of interface with interdependent two-way effect.

#### **External Shared Resources**

External shared resources are the elements outside the system boundary which do not interact with the system/sub-system but do provide vital information for the system in the form of input.

#### **System Overlaps**

When two or more sub systems share the common object or group of objects (most of the time in complex systems) this is known as System Overlap. It is important that the overlap must be indicated where ever it is identified because if the overlap is not indicated then this could be the cause of the potential failures.

## **Object**

An object is an information package containing a name and brief, but accurate description of the design intent of a separable part of the system. In OO-FMEA there are three types of objects, which are physical, attribute and logical objects.

### **Logical objects**

The Logical Objects are represented with red squares and are software based which are responsible to perform different tasks such as taking different decisions to have the operations performed according to the requirements set by the user and instruction from the Climate System for the required/set climate comfort in the passenger compartment.

### **Physical Objects**

The Physical objects are represented with blue squares which represent the hardware or tangible devices which take part in the completion of any process, e.g. electric control unit, relay, switch or sensor etc.

### **Attribute objects**

The attributes objects are represented with a green square, which define the attributes of the design intents of the logical and physical objects. Basically the attributes objects holds the desired conditions and quality level of system, subsystem or to which it refers to. The examples of attribute objects are crash handling, legal requirements, passenger's protection, system performance, prevention against noise factors etc.

## **Design Intent**

The design intent of an object basically shows the perception about the working of the object in the system, it explains what does this object do and what is its purpose.

## **Topology**

Topology is the geometrical arrangement of modules and units in the network.

## **LIN**

LIN is single wired low cost, low speed having a data rate of up to 20 Kbps asynchronous bus used in the products for non-critical applications.

## **CAN**

CAN uses unshielded two wire line, medium speed a synchronous bus having a data speed of 1 Mbps a medium speed asynchronous bus offering a data rate up to 1 Mbps.

## **Flex Ray**

It is a serial communication and uses two channels, both of these channels have pairs of wires, and it has the data transfer rate up to 20 Mbps and it has a payload consist of 0 to 254 bytes for the transfer of data

## **Severity**

It represents what is important to industry, or to customers such as the safety standards, loss of functions etc. It shows how severe the failure is so 10 means the very high severity ranking when a potential failure mode affects the

safe vehicle operations and 1 being the lowest and to be less worried about.

### **Occurrence**

It is the probability of the occurrence of failure during the expected life time of the product. In other words, how often this failure may occur or occurs and is based on the previous failures. 10 is consider having a high persistent failure and it can be defined as 100 products out of 1000 products if the problem occurs and 1 being the lowest such as 1 product out of 1000.

### **Detection**

It is the detection of the failure in the product and is based on the internally defined criteria. On a ranking scale 10 being very hard to detect and 1 being easily detectable.

### **Risk Priority Number (RPN)**

RPN is a decision factor based on the product of three ratings which are severity, Occurrence and Detection based on the standardized criteria. These ratings are scaled with numbers from 1 to 10. According to the criteria there are different levels of acceptance of the Risk Priority Number.

### **Abbreviations**

AC	Air Condition/Conditioning
ACCM	Air Conditioning Control Module
AQS	Air Quality Sensor
AWD	All-Wheel Drive
BCU	Battery Control Unit
BECM	Battery Energy Control Module
CAN	Controller Area Network
CCM	Climate System Module
CCSM	Central Console Switch Module
CEM	Central Electronic Module
CISG	Crank Integrator Starter Generator
CPM	Combustion Preheater Module
CPSR	Charge Power Sustain Relay
DC/DC	Direct Current to Direct Current (high voltage DC to low voltage DC)
DIM	Driver Information Module
ECM	Engine Control Module
ECU	Electronic Control Unit
ERAD	Electric Rear Axle Drive
FMEA	Failure Modes and Effects Analysis
FOH	Fuel Operated Heater
HBMF/R	HVAC Blower Module Front/Rear
HMI	Human Machine Interface
HS CAN	High Speed Controller Area Network
HUS	Humidity Sensor



HVAC	Heat Ventilation and Air Conditioning
HVCH	High Voltage Coolant Heater
IEM	Inverter ERAD Module
IGM	Inverter Generator Module
IHU	Infotainment Head Unit
ISC	Inverter system Controller
ISG	Integrated starter generator
LIN	Local Interconnect Network
OO-FMEA	Object Oriented Failure Modes and Effects Analysis
PT	Power Train
PTC	Positive Temperature Coefficient
RPN	Risk Priority Number
SHML/R/FL/FR	Seat Heating Module Left/Right/Front Left/Front Right
SPA	Scalable Product Architecture
SUS	Sun Sensor
TEM	Telematics Module
TXV	Thermal eXpansion Valve
VCC	Volvo Car Corporation
VDDM	Vehicle Dynamics Domain Master
Vlv.	Valve
VMM	Vehicle Mode Management
TPS	Transaction Processing System
DPS	Data Processing System

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# 1 Introduction

## 1.1 History

The technique of Failure modes and Effect Analysis (FMEA) was first used in 1920's but was not considerably documented. Afterwards in 1949 it was used for military procedure MIL-P-1629, in which the FMEA was performed it was used as a reliability technique to determine the effects of the system and equipment failures. In 1960's FMEA was used to improve and verify reliability of space program hardware [1]. After that in 70's it was introduced and used in the automotive industry but its use was geared up in 90's to cope with the major quality and reliability challenges [2]. The wide use of FMEA methodology is being made possible by the recent changes in the law on corporate responsibilities.

## 1.2 Motivation

Automotive industries are introducing intelligent vehicles for the sake of customers' comfort. To be stable, to propagate in the market and to compete with the contenders, there are certain requirements to be fulfilled [3], quality is the basic one of those requirements. To produce reliable and high quality products companies have product testing workshops in which the preexisting models and/or the prototypes of products are tested and decisions regarding any changes or up gradation are made based on the tested data [4]. Getting a physically tested data to mitigate the failures and errors is considered late if production process of any product is started, because after that the customer will be directly affected [5]. This is where FMEA come in handy, because FMEA is started in the design phase and by the time the prototype is completed almost all the failures and errors are already been reduced or eliminated. In simple words FMEA is a process to eliminate/reduce to errors before even they occur [6].

FMEA is the process which can be described as a systemized group of activities intended to recognize and evaluate the potential failure of a product/process and its effects, to identify actions which could eliminate or reduce the chance of potential failure occurring, and documenting the whole process. Though being famous and widely recognized still some improvements are required the FMEA process alone is not very much capable of delivering the results which can be resulted by the implementation of several operations performed with FMEA to have better results. For this approach to work better there are several different processes which should be performed along with FMEA to get better results which could not be provided by FMEA alone [7] . It is complementary to the process of defining what a design process must do to satisfy the customer. Failure Modes and Effect Analysis (FMEA) is a logical and systematical analysis of a system, sub system, module or object to analyze and identify the failure modes their roots and the reasons which cause them, and the effects related to those failures [8].

### 1.3 Problem Definition

In order to make the products more reliable, robust, efficient and long lasting, the products must be developed while keeping in mind all the possible failures modes. Less the failures are, less are the chances of the product go fail. According to Murphy's Law "**Everything which can fail, will fail**" [8]. So it is almost impossible to make something which never fails, but the life of the product can be increased and for that FMEA has been in use. The technique of FMEA is around since the beginning of 20<sup>th</sup> century. It has been very useful for the betterment of product quality. As there is always room for some improvement in the products, so is true for the tools which are in use to make these products better and improved. FMEA is a good and efficient approach but only when it is implemented on simple systems. This approach is not very good to find the missing or incomplete designs. It does not focus on the interactions and interfaces between the objects, sub-system and even systems [9]. So performing FMEA on such complex system can be a tedious task. In complex system the sub-system often has the overlaps and their boundaries are unclear. Though FMEA is around for a long time but still only FMEA is not a very good approach when it comes to the complex systems. For the complex systems we use OO-FMEA. Climate System is a complex system and OO-FMEA is the approach to be implemented on it. The main objective of this thesis is to implement the OO-FMEA and generate the failure modes to have better results. OO-FMEA being a five steps method, the steps which differentiate the traditional FMEA from OO-FMEA are steps number 1, 2 and 3, whereas step 4 and 5 are same as of traditional FMEA [9]. It is more efficient and is more feasible, relevant and effective towards the complex systems, efficient in the detection of missing or incomplete designs, unclear or unnecessary requirements and specifications which cannot be identified when applying the traditional FMEA approach are identified. The best thing which makes OO-FMEA dominant on the traditional FMEA approach is that the objects are convenient for reuse and update [2]. This makes it possible to understand the boundary of the system to be considered and understating the complex failure modes and the failure modes in different subsystems.

### 1.4 Aims and objectives

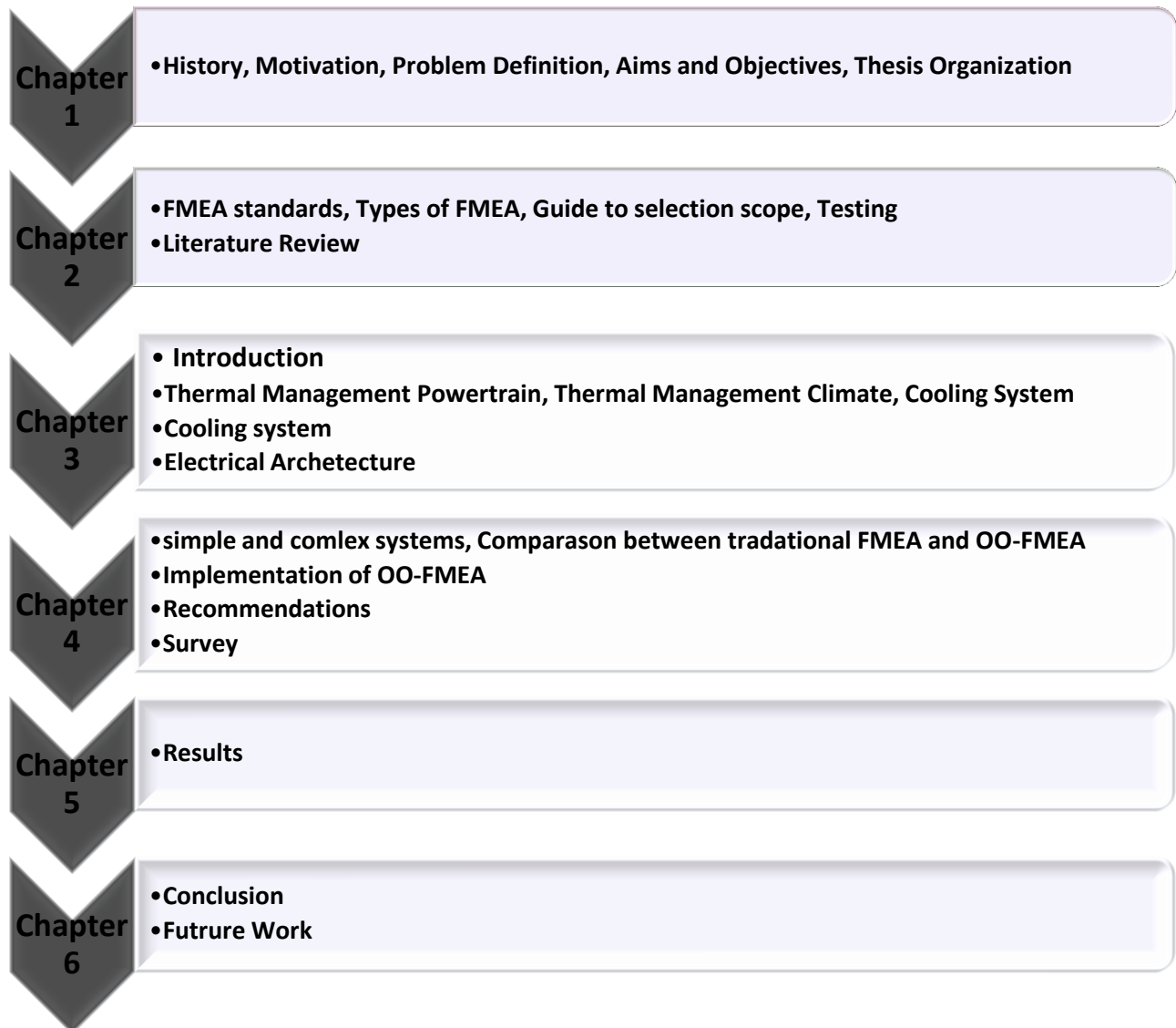
The main focus of this thesis work is to apply the OO-FMEA approach on Thermal Management Climate in order to study the effectiveness of the new approach in analyzing complex system. As Thermal Management Climate is a big and complex system and traditional FMEA is not very efficient for this kind of system that is why OO-FMEA is being applied on this system. Within this system one of the functions, defroster is chosen as an object for detailed analysis in this report according to the principles of the new approach. The main objectives which will be achieved by the end of this thesis work are as follows,

- Advantages and disadvantages of using the OO-FMEA instead of traditional FMEA approach.
- The capability of this approach to identify
  - Incomplete designs
  - Ambiguous and unnecessary requirements (Suggestion related to them)
  - Unmotivated complexity in design solutions

- Undesired external sub-systems interactions and interfaces
- Easy usability
- Easy update

## 1.5 Thesis Organization

This thesis report consists of 6 chapters. Chapter 2 describes about traditional FMEA, its standards and types, testing and literature review. Chapter 3 describes about Thermal Management climate and powertrain, Chapter 4 describes about implementation of OO-FMEA and recommendations. Chapter 5 is all about the results. Chapter 6 covers the conclusion and future work



## 2 Traditional FMEA

### 2.1 FMEA

It is a tool for risk assessment, a function or a systematic process which is used to identify potential failure modes and their causes, and for the improvement of product reliability [10]. It also evaluates the effects of the failure or errors in the system and provides the information of the system about the capabilities and limitations of the system. It helps to mitigate or minimize the risks related to the failure modes. Under given conditions “*Failure*” is defined as the loss of envisioned function and the way it occurs is termed as “*Failure Mode*”. The penalties as a result of the Failure are termed as “*Failure Effects*” [11] .

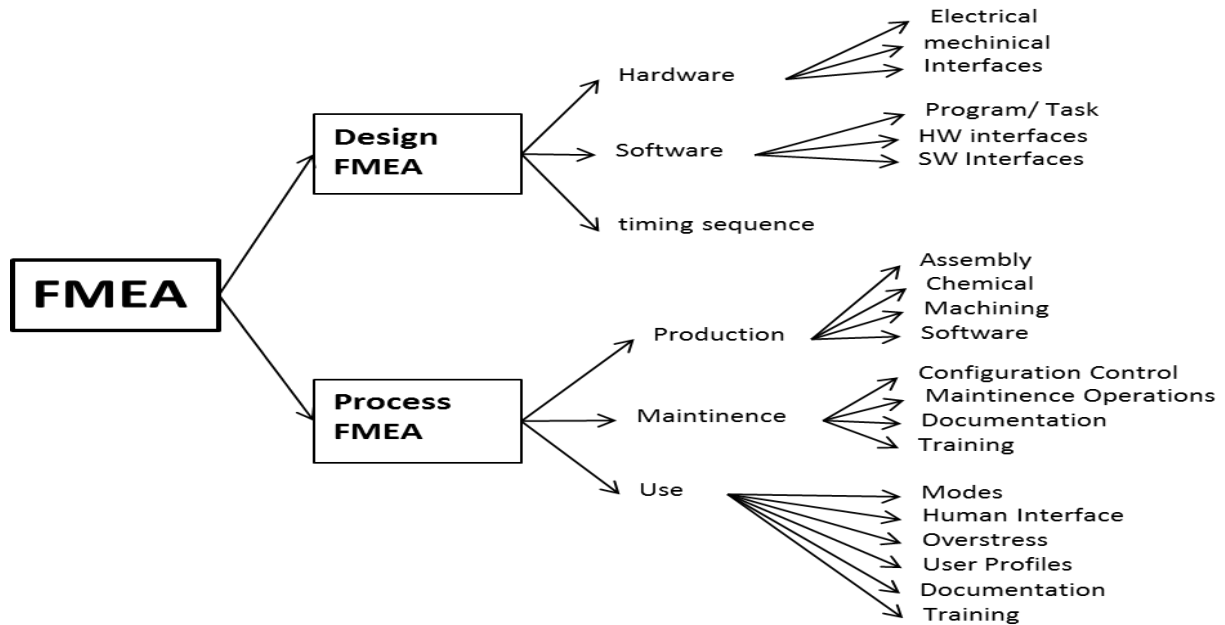
One advantage of FMEA to start early is that, it makes it possible to understand any requirements for the project and these requirements are added in the product before it is finalized (Earlier it is, the better it is). The basic objective and purpose of FMEA is to help in developing a system which is without or very much reduced potential failures or errors and the system which can tolerate the failures and faults in any given circumstances and conditions. Aside from those the focus is not only to develop a fault tolerant system but also to allow the faults or errors to be corrected to some extents when they occur and it must not affect the system or its performance. In any automotive system, all the basic and general systems and sub systems are involved and are taken under study for the development of a more robust system which can cope with any problems and failures the system may face. Each and every minor detail is taken under consideration during the FMEA process, only then can a system be more efficient [8]. The actions against the failures and errors are taken according the standards set by the organization and for the required quality of the product. Any system which has to perform in an environment where it has more chances of facing the errors and failures, for those areas the system made is more robust and efficient enough that it could face any challenge and any problem. Even if the problem occurs, the system should have the ability and capability to cope with it. Such system to be made the FMEA is a tool to be used in the design phase so that the errors and problems, which the end product may face in future, should be eliminated in the design phase which is more time, money and energy efficient [12].

#### 2.1.1 FMEA Standards

There are some standards on which FMEA is carried out and those are important to mention. These standards provide the basic structure and manner in which FMEA is to be carried out in matter of severity, detection and occurrence. Various industries have established their own standards, such as Aerospace and Defense companies follow MIL-STD-1629A. Automotive industries usually follow SAEJ\_1739 or AIAG (Automotive Industry Action Group) which is basically the combination of different standards which includes SAE J2886. International Electro-technical Commission adopts IEC 60812 [8].

### 2.1.2 Types of FMEA

There are two types of FMEA processes i.e. Design FMEA and Process FMEA. In Design FMEA analyses the design of the system, information about the material used, information regarding the satisfaction and/or specifications, government regulations etc. whereas Process FMEA analyses the potential failures during the manufacturing process, machines and other production methods. The FMEA hierarchy is shown in the figure 2.1 below [13],



**Figure 2-1 Types of FMEA**

### 2.1.3 Guide to the Selection of Scope

There is no such time limit when it comes to the starting of the FMEA but to get the full advantage and better results the FMEA should be started in the design phase. Design engineers recommend starting the process between the defined phases. A guide line is developed for that purpose which shows the recommended areas of focus in the FMEA at different phases of product development [2].

If the FMEA is started between the concept and system phase the main focus should be on the system design including the functions, causes including the behaviours and legal requirements from the concept phase.

- Concept Design

At the concept phase of product development, the main focus is on the basic functions, what kind technology is to be used, the use causes and legal requirements.

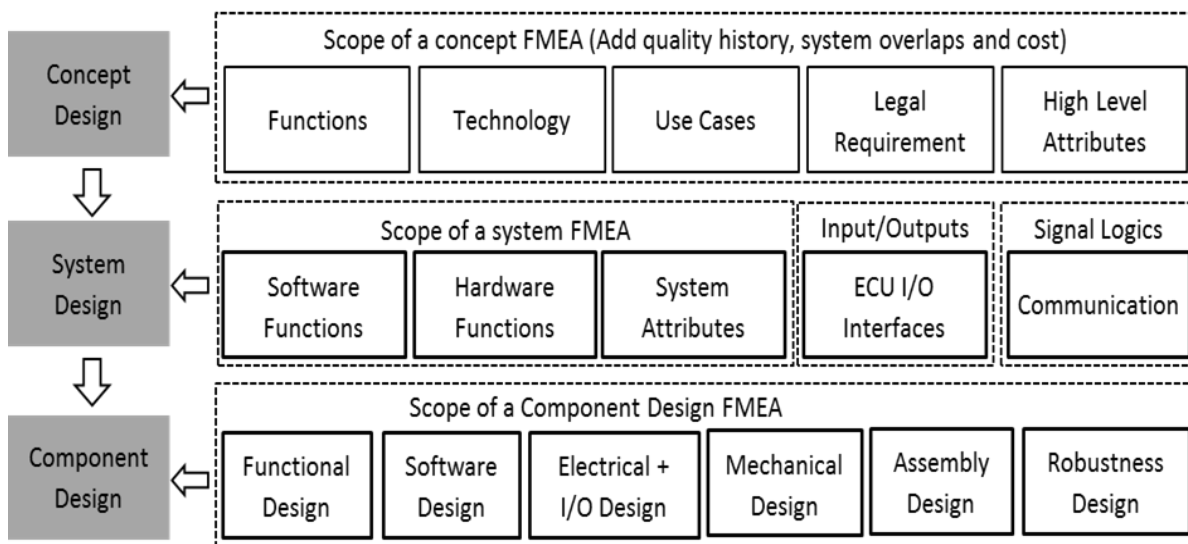
- System Design

System design being a complex design level is composed of at least three level of analysis. From the figure 2.2 normal scope of the system FMEA is shown which includes the software, Hardware and attributes.

For complex modules, such as CEM or ECM, or any other composite modules having multiple I/O interfaces, the appropriate approach is to consider the whole set-up of connected components with control unit as one system. The other view of the system analysis is to analyse the system from the perspective of signal communication and reliability (Signal Logics).

- Component Design

Even though this instruction primarily emphasises on the concept and system design, but the principles can also be used for the complex component design. In case of complex modules the component design phase has its own internal structure and behaviour.



**Figure 2-2 Guide line for choosing the FMEA scope**

For the development of any product there are some rules and principles defined such as planning of the product which may include the prioritization of the objects by the engineers, task leaders, managers etc. [1]. The development team raises and studies the questions, identifies the issues related to the system and generate the possible failure modes. The important thing which should be kept in mind is the simplicity of the design, simpler the design is, simple it is to understand it and work on it. Another important thing is to document each and everything which is being done, explained, discussed, suggested or tested during the process of FMEA. The documentation regarding FMEA needs to be updated wherever there is a change made. Doing so will help to understand the effects on the system due to these changes. Suitable intervals should be taken for any update to be made in FMEA. [8]



#### 2.1.4 Testing

Testing plays an important role in the performance of FMEA (if possible), because most of the time the FMEA is done in the design phase of any product, as the product is not even developed yet so physical testing is not possible (most of the time). The FMEA can be differentiated from the physical testing with the help of following diagram,

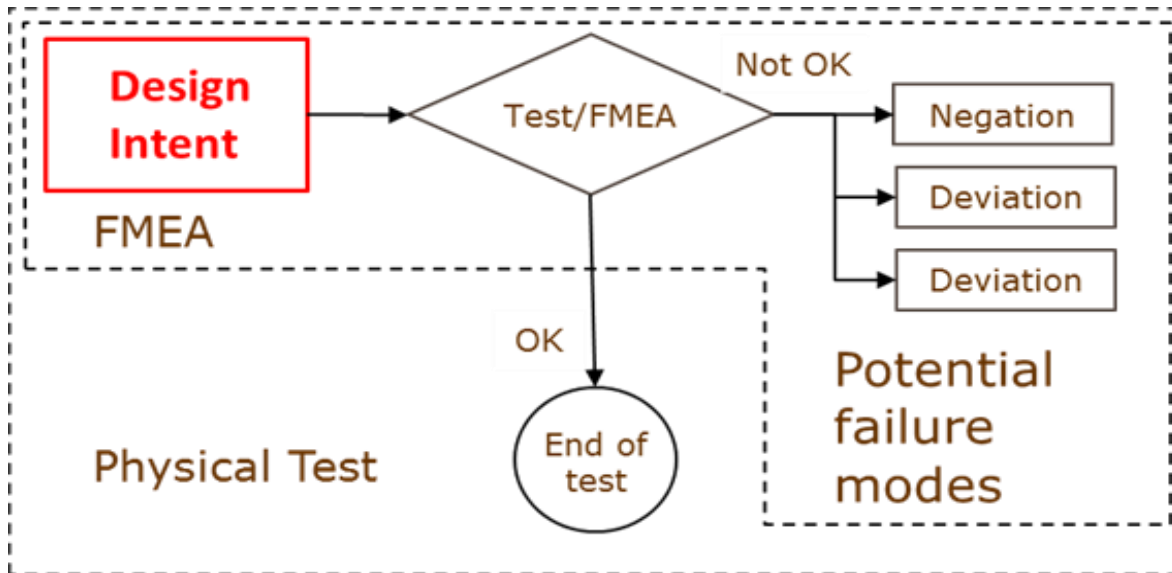


Figure 2-3 Difference between the Physical testing and Theoretical testing (FMEA)

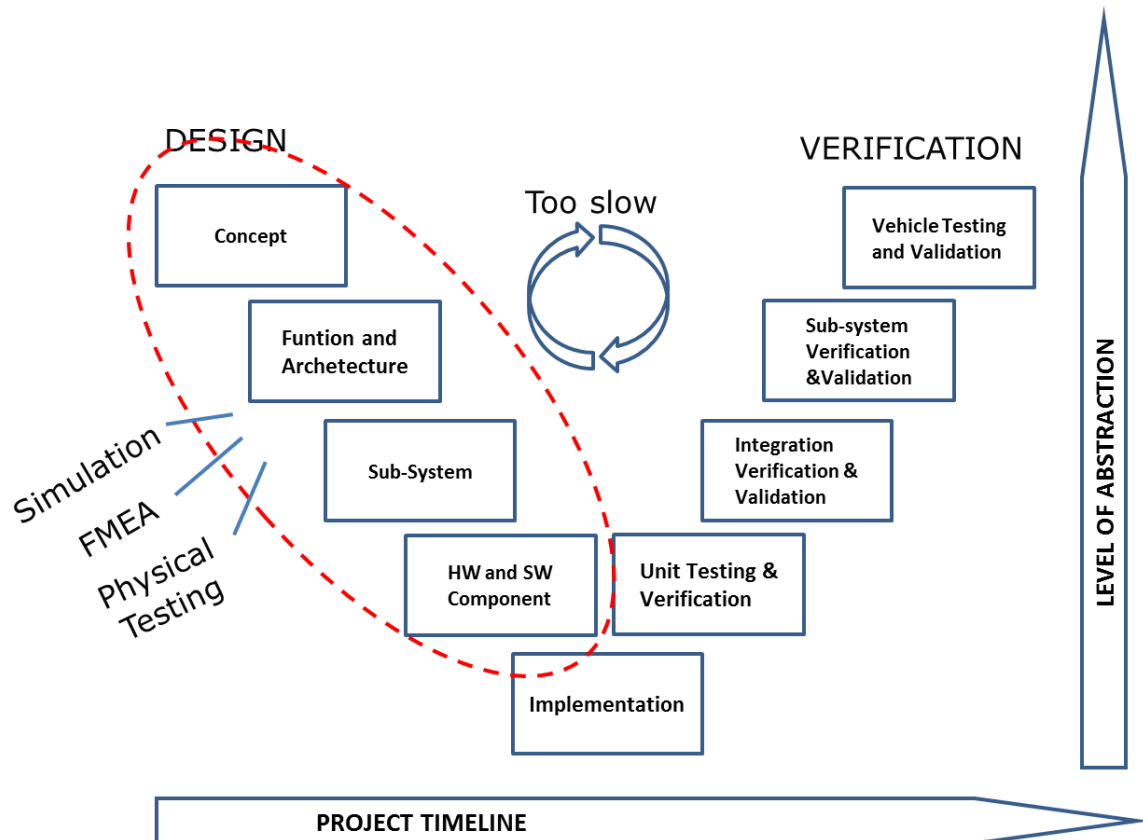
The testing can be physical and theoretical; the physical testing includes the testing either on the product prototype or developed product, whereas FMEA itself is the theoretical testing. During the FMEA the failure modes of any product or system are identified / studied and that is what the physical testing does [5].

In the FMEA process there are many types of failure modes which are being learnt and found which affect the system in different ways [6]. If these failure modes are left undetected could affect the system badly may result into total destruction. As the FMEA process is documented at every bit and pieces level so when an unacceptable failure mode is identified, the report or documentation regarding the failure mode should be forwarded to the designer so that it could be fixed in the design phase [8]. If something goes undetected, it may be noticeable to the clients, so to avoid anything like that detailed review of FMEA must be completed before it is sent to the designers.

Whenever the FMEA is concluded the solution is explained and discussed with the design team. According to the requirements from the owner, the owner is told about the results and what kind of changes and up gradation may be required to have a system with less errors, and if the changes in the existing design are required then it depends on the owner whether he wants to change it or not. If it is the matter of small changes which lead to greater good then this is discussed with the design team and the decisions are taken [8].

### 2.1.5 FMEA in modern project development line the “V-Diagram”

The FMEA is a process which should be started in the design phase to achieve best result and reduced engineering time and energy. In the design phase there are different stages and which form hierarchy with respect to time line and the level of abstraction. In the design phase the first thing that comes at the beginning and at the most abstract level is the concept of the product. The concept is an edifice to any product or project to be developed. The concept phase describes the product abstract, along with the reason of the product which helps achieving the real goals of the product [9].



**Figure 2-4 FMEA in a modern product development process (The V Diagram)**

Following the concept phase, comes the architecture and functions of the product. This goes more deep into the product describing its detailed functions and the architecture. At this stage the product is not yet started or developed. This phase is still the abstract phase, though it has got the some shape of the product but still it does not describes the product completely.

In the next phase the product is defined at the system level where the system and the sub-systems are described based on the functions and at this phase the product takes some shape. The design phase is basically the collection of four stages and all the actions such as, Simulation, FMEA and Physical testing is done here. As the product is not completed yet but definitely it has got some shape and prototype as the next phase goes more deep towards the development of software and hardware components. Next phase is the implementation phase

in which the implementation of the products is done. In this phase all the previous knowledge data is used to shape the product. From the implementation phase the level of abstraction rises as the project timeline proceeds towards completion.

## **2.2 Literature Review**

Since the start of FMEA there has been a lot of research on the making the FMEA process more efficient and for that much research is carried out. Though traditional FMEA has its history and have been useful but still there are always some flaws and room for up gradation. OO-FMEA is a 5 step method which insists on the system structure or boundary, the interactions and interface between the design intents and the prioritization of the objects. These are the steps which make OO-FMEA more robust and efficient. Methodologies of FMEA are discussed which shows some of the drawbacks

1. As a survey method FMEA most of the times is very useful to identify the major failure modes of any system. FMEA is a useful tool but this very tool is not able to cope with the complex system and to determine complex failure modes which involve the multiple failure modes and failure in the subsystems due to the absence of interaction and interface. It is also not very good with the estimation of the reliability of the product [12].
2. Nematollah Bidokhti (2009) highlights the incompleteness of FMEA and represents the steps and methodology that is required to be followed before and/after FMEA to take its full advantage. According to him there are some requirements which important for a system to robust. These requirements include reliability, availability, detectability, isolation and fault coverage. Fault management architecture of any product is of great importance so when it comes to next generation of pre-existing product the fault management architecture is addressed but it will be very challenging if the product initially did not have built in fault management because then it will require an overly architecture. For new products fault management architecture must be built to avoid problems later on.

First step includes the utilization of the information provided by the customer and marketing team to develop the requirements. In second step it is made important to work with engineering, architecture and design teams to make sure that the key elements are identified also incorporate these in hardware and software architecture. Third step: Creation of failure modes classification and execution of FMEA. Having a comprehensive list of hardware and software failure modes is critical to the success of a reliable design. Depending on the types and levels of the FMEA, there is already taxonomy that addresses the hardware failure modes. Fourth step: the implementation of Fault Insertion Test (FIT) and use FMEA as FIT test plan. [7]

3. According to Milena Krasich (2007) criticize FMEA, that this approach cannot be considered a standalone approach in a reliability program.  
Traditional FMEA treats each and every failure mode independently. So when the analyzing reliability of a failure mode is concerned, FMEA is not efficient. Either FMEA has to address all the components else the quantification of probability of failures of

entire product is not likely to be. Due to the lack of knowledge about the interactions and interface between the objects as a result this method of analysis is good for some improvements but not to discover the expected failure mode in product for a particular failure mode.

The inputs for FMEA include the electrical and/or mechanical engineering analysis along with the failure rates and failure probability of the under study system which helps understand the severity level of the failure modes. Study of reliability test design, testing and data analysis of the system. These studies lead to the outputs in the form of archives of the failure modes found suggestion regarding the required and taken actions and what are the measures taken to reduce the failure modes.

FMEA treats each failure mode as independent which does not show its relations or dependencies over the others, and because of this FMEA cannot produce trustworthy information regarding the product reliability. (this problem is taken care in OO-FMEA due to the identification of interfaces and interactions)

If FMEA only addresses some of the components and their failure modes, the behavior of the entire system cannot be understood and the analysis can never be considered complete for the entire system. This is due to FMEA procedure as it treats every failure mode independently which does not show its relation or affect over the others. (again this is taken care of OO-FMEA which the prioritization is done based on the interactions and interfaces). [10]

4. Software development using Unified Modelling Language (UML) mostly provides products that deliver more transparent overview of the system. Eradication of failures of single output is not agreeable as it may miss many conditions in which a single programming error affects multiple variables. These are some of the basic reasons which require the generation of software FMEA. It helps much as the FMEA generated in response to this helps in validation and verification. UML can be of great assistance as it helps to look deep into all forms of dependability analysis of methods (Behaviors) in the system which are completely characterized. Verification and Validation is no doubt a costly process and software based FMEA can help by highlighting the objects having high level of severity, so that those objects should only be focused with a confidence that it would eradicate the failure modes. As far as the question of missing links or data is concerned detection level can help defining the attention level.

Implementation of FMEA in concept phase is much better as the highlighted weaknesses can still be corrected without the documentation which is required if the implementation is done in later phases. Computer generated FMEA can benefit much even if it is incomplete. In this approach a use case diagram is used with a role assignment. Role assignment is a software construct. Wherever components are automatically switched from active to standby status role assignment is confronted. The use case diagram is usually the first item created in UML-based development whereas the stick figures are called “actors” and are not necessarily persons, could be a control system.

UML development tools such as Rational Rose™ and Rhapsody™ could be of great help in conducting the analysis with reduced efforts. The Use Case Diagram could be generated by these tools which also store the structural information and properties as part of their database with the help of which the program for computer aided FMEA can be recovered. During the implementation phase higher degree of integration between FMEA generation and UML tools are achieved.

In this phase FMEA is done on the system and decisions are made on the basis of the findings (Failure modes). In this phase the Identification Number (ID) is assigned in a manner of aa.bb.cc.dd and these are configuration items. Based on the nomenclature failure modes are identified by the letter such as “s” for stop or “I” for incorrect result or by numeric suffixes.

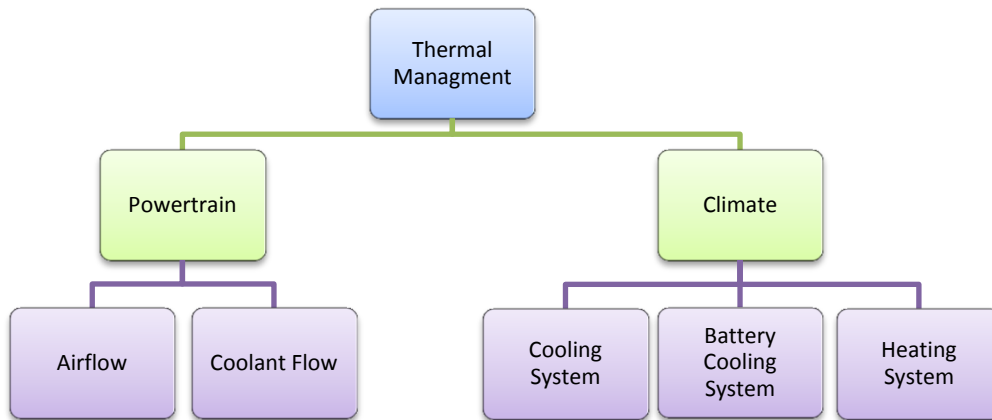
There are listed over 20 different types of failure modes based on their types e.g. hang, stop, missing data, incorrect data or wrong data etc. these are necessary for software FMEA as there can be a variety of failure modes.

Milena Krasich (2007) criticize FMEA that traditional FMEA treats every failure mode independently due to which its relation and dependencies over the others is not clear in other words the combination of failures are captured as a single failure. So its affects cannot be studied and thus traditional FMEA cannot produce reliable information regarding the product reliability. If FMEA addresses some of the components and their failure modes, the behavior of entire system cannot be understood and analysis can never be considered complete. Nematollah Bidokhti (2009) highlights the imperfection of FMEA and suggests that alone FMEA is not good enough to handle complex system, and some steps and methodologies are required to be followed before and/or after to take full its advantage. Katarína RIPLOVÁ (2007) highlights that FMEA is a useful approach but it is not very useful when it comes to complex systems. FMEA is not able to notice complex failure modes at multiple levels of details and expected failure intervals of failure modes and for these different other methods such as Fault Tree Analysis (FTA) are used.

# 3 Thermal Management

## 3.1 Introduction

As the name shows Thermal Management is the high level management system of the thermal energy in the vehicle. In electrical, mechanical, both or any other systems when some work is done it gives rise to the output and also heat is produced as a byproduct due to friction or other reasons, which affects the efficiency of the system or damage the system/components [14]. To overcome this problem or make use of the excessive heat, thermal management system is used which maintains the temperature where required and also it gives heat where required in an extraordinary fashion [15]. Also it helps to use the waste heat for any functions in the vehicle, such as the heat in the winter season is basically the usage of the waste engine heat which is processed to make it useful though sometimes heaters in the air vents are also used but it is not a very good idea comparatively. In the Vehicle structure it is used to control the heating and cooling the actuators, consumers like engine, climate and the hybrid components like ERAD (Electric Rear Axle Drive), high voltage battery system etc. Due to organizational dependencies the thermal management is described in the hierarchy shown in the figure below.



**Figure 3-1 Hierarchy of Thermal Management at VCC**

Thermal management at Volvo Car Corporation (VCC) is composed of two parts i.e. Thermal Management Power Train and Thermal Management Climate. The power train side is further divided into two sub systems, Air Flow and Coolant Flow Engine. Similarly Thermal Management Climate is divided into three sub systems, cooling manager, heating manager and battery cooling system [16].

Cooling is responsible for providing the cooling of all the components and passenger compartment. There is a separate loop which is called as A\C loop in which refrigerant flows

and provides cooling (mentioned in cooling module). Battery cooling system though has its separate coolant loop but when alone coolant flowing in that loop cannot fulfill the requirements then there is present a chiller in the A/C loop which helps fulfilling the requirements which is activated with the Chiller Shutoff Valve being activated by the Climate System Module.

Where in case of heating there are two options, i.e. the management of excessive heat from engine and in case when the engine is not started yet (preconditioning) the heating is done with the help of the HVAC heaters.

## **3.2 Thermal Management Powertrain**

It is the sub-system of thermal management and is further divided in to Air Flow and Coolant Flow System.

### **3.2.1 Air Flow**

The air flow system helps the cooling or heating to reach the user. There are different levels of the flow of air according to request from the user as well as to maintain the climate comfort. The air flow on the whole is a system which provides the required airflow to the systems and subsystems. During the high loads on A/C system when more cooling is required, the condenser might require the airflow to help fulfilling the request. Engine also require the airflow to help lower down its temperature but it has high current consumption and noise level, due to which it is only used when it is required to the most or is used in balance with cooling from coolant flow. There are shutters present to get the outside air when required and should remain closed to avoid aerodynamic drag. In winter these are most of the time closed but in summer are open most of the time until vehicle high speed. To lower down the temperature in electric drive train, the fans are used.

### **3.2.2 Coolant Flow**

The cooling system of the powertrain components in a hybrid vehicle is divided into three different levels based the temperature limits at which the cooling is required [16].

- Low Temperature Cooling Circuit, includes the cooling of the High-Voltage battery
- Medium Temperature Cooling Circuit, includes the cooling of ERAD
- High Temperature Cooling Circuit, includes cooling of Engine

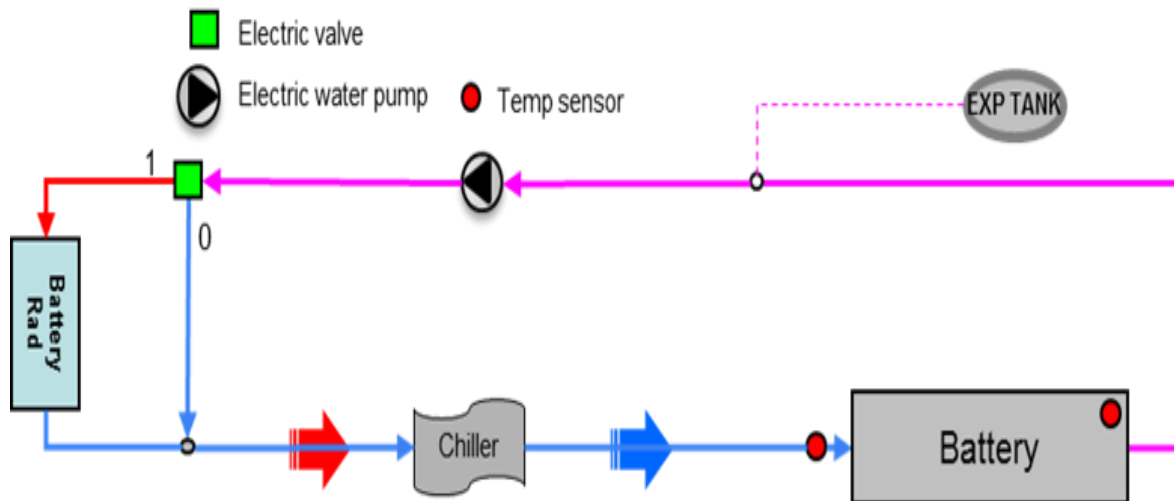
### **High Voltage Battery Cooling**

High voltage battery cooling system comes under the area of low temperature cooling components, where the maximum specified temperature limit is 32 °C [17].

#### **Components involved in the high voltage cooling system**

1. Water pump, Located behind the high-voltage battery
2. Air cooler, located under the floor on the right hand side
3. Expansion tank, located above the right hand wheel housing
4. 3-way valve, which opens for cooling at 32°C

There is a separate cooling system for high voltage battery as the battery requires the specified temperature ranges with the upper limit of +32°C, and battery's control system strives to maintain the temperature of the battery cells [17]. While driving the cooling starts when temperature exceed +32°C and the cooling process stops when the lower specified temperature is reached, whereas this cooling limit is reduced to some more degrees lower than the specified lower temperature when the car is connected to the electrical network so as to minimize the cooling requirement during driving and somehow the lower temperature during charging is to extend the service life of the battery [16].



**Figure 3-2 Battery Cooling Loop**

#### Battery Control Unit (BCU)

BCU is a 2-circuit system cools the high voltage battery with a specified cooling capacity by the process of evaporation of refrigerant from the A/C system and cools the coolant water at a 22 fin heat exchanger. BCU is located in the tunnel under the floor and is protected from the exhaust system using heat shields.

#### Battery Energy Control Module (BECM)

The BECM controls the two coils of the high voltage battery's cooling system via a 3-way valve. The 3-way valve opens and allows the coolant to circulate in to other cooling coil, which is cooled by the refrigerant from the A/C system in the BCU, as soon as the temperature of the battery cells exceeds the +32°C.

#### **Electric Rear Axle Drive (ERAD) Cooling System**

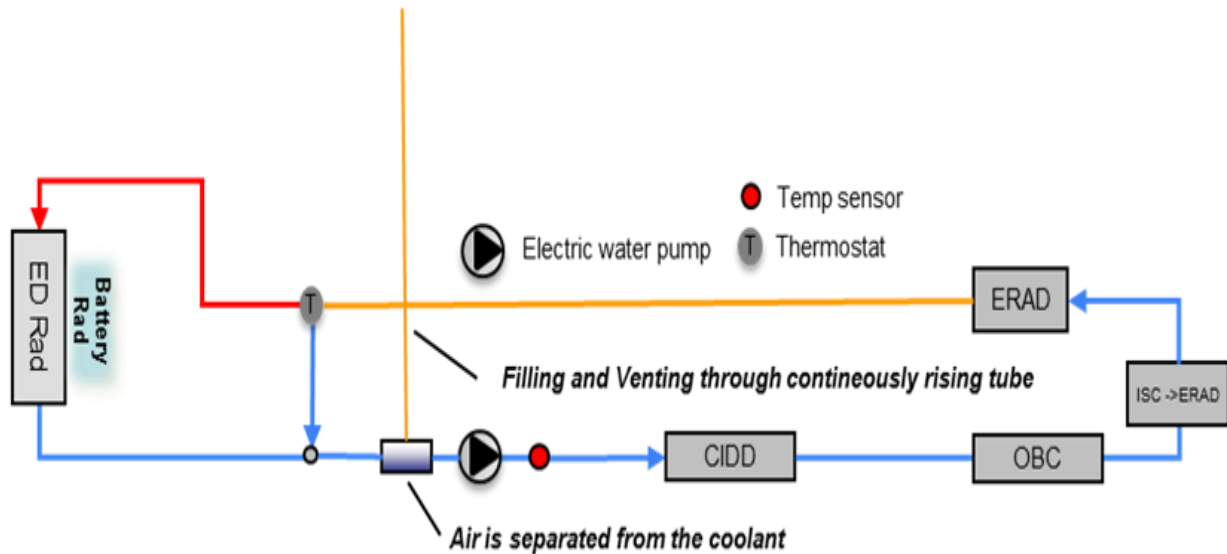
ERAD cooling system comes under the area of medium temperature cooling components, where the maximum temperature is set to a certain limit which is considered as a medium



temperature as compared to the temperature ranges of Battery and Engine temperatures and [16] also is responsible of cooling the components like OBC, DCDC, ISC and ISG [16]. Following are the components which are required for the ERAD cooling system,

The medium temperature cooling system is regulated by the ECM using 3-way valves, temperature sensors and an electric water pump.

1. 3-way valve - Low temperature cooling system, engine coolant
2. Electric water pump
3. 3-way valve - radiator or bypass
4. Thermostat
5. Temperature sensor

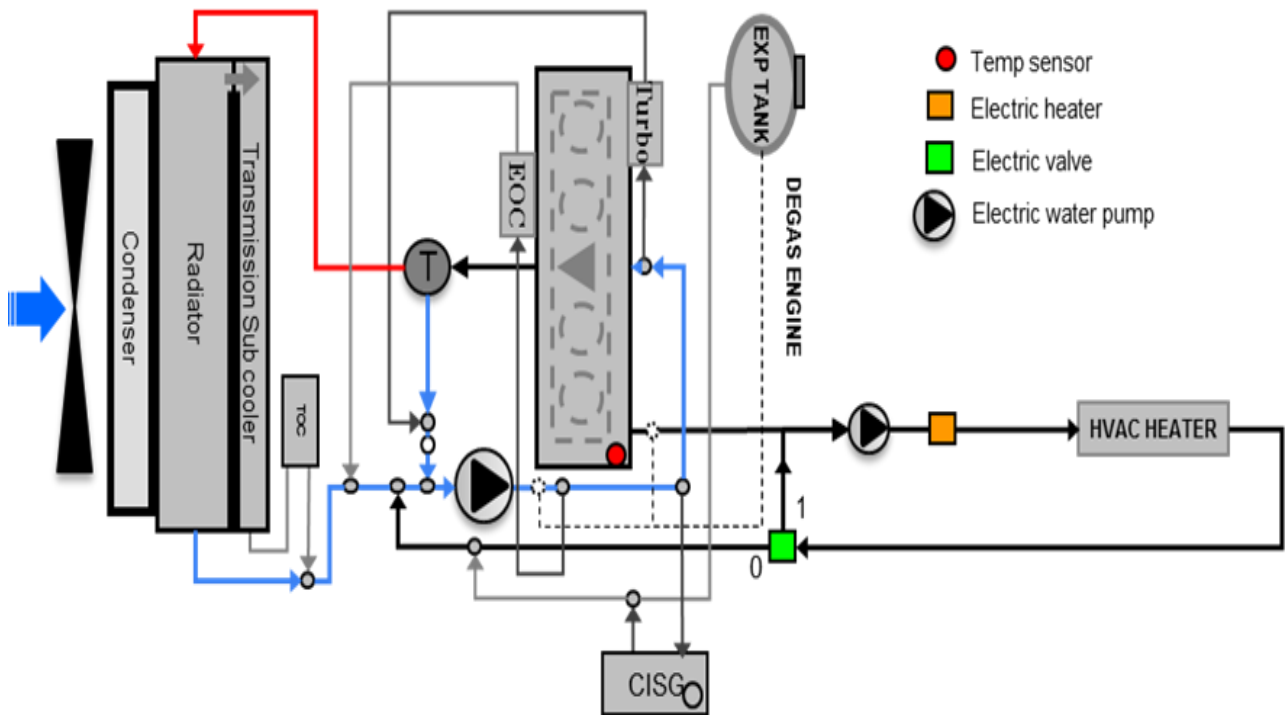


**Figure 3-3 Electric Rear Axle Drive Loop (ERAD)**

### Engine cooling system

In the engine cooling system internal Combustion Engine Circuit, the temperature sensor present in the engine reads the temperature, the hot coolant flows out of engine and passes through the thermostat, the thermostat is set at some threshold [16]. If the temperature is less than the threshold then is sent to the electric pump from where it is sent back to the engine, but if the temperature is above the set threshold then is sent to the radiator where the coolant is cooled down and also there is present a fan which helps the radiator to cool down even some more. From there the coolant goes to the same electric pump and is sent to the engine to lower the temperature of the engine. In this loop the maximum temperature must never go beyond a specified temperature. Along with this coolant there are some other components which also are cooled down like there is transmission oil coolant and Engine Oil Coolant. There are present the venting valves which are used to degas all this process, by letting escape the air from the coolant even steam so as to avoid the extra pressure which is building up in these tubes. These venting valves lead all the way to the expansion tank to complete the degasing. After the electric pump there is a connection to the Crank Integrated

Starter Generator (CISG) which operates a starter moment and also generates 400V to high voltage system and when the coolant passes through it goes back to the electric pump.



**Figure 3-4 Engine Cooling System**

### 3.3 Thermal Management Climate

The Climate System is basically the management and maintaining of the temperature (climate) which is set by the user under all the condition. When a certain temperature is chosen by the user, climate system controls it according to the changes in the ambient temperature, humidity, vehicle speed etc. The Climate System can be preconditioned in the car, which means that the passenger compartment and the engine can be heated or cooled down and the high voltage battery can be cooled down (*or heated, though the heating of the High Voltage Battery is not done yet but it is being presented by as a suggestion*) before the car is used. The electrical components need a controlled operating temperature and therefore have an independent cooling temperature.

#### 3.3.1 Preconditioning

The heating up or cooling of the passenger compartment before the car is in use is called as preconditioning, it also includes the heating of the combustion engine and cooling of the high voltage battery if there are any conditional requirements. Depending on different climate conditions the user uses this function to make the passenger compartment according to comfort.

### **3.3.2 Defroster**

The use of Defroster in the vehicles is of great importance. The defroster is a manual function which is activated by the user manually when the need of it is felt. When the humidity level reached the dew point and forms the mist on the windscreen then it becomes hard to see through the windscreen. The driver turns ON the Defroster so that the mist on the windscreen as well as on the side windows is reduced [2].

### **3.3.3 Head Level estimation**

Head level temperature is the closest temperature to climate comfort (desired temperature) and its estimation is done in the Climate System. It is calculated based on the data values from the ambient temperature, sun sensor, speed of vehicle, in Car sensor and evaporator temperature sensor. Based on these calculations for the head level estimation the climate comfort is estimated [16].

### **3.3.4 Steering wheel and Seat Heating**

Climate System also includes the seat heating and steering wheel heating but to make the system more simple it is been included in to component heating and is included in to another system [16].

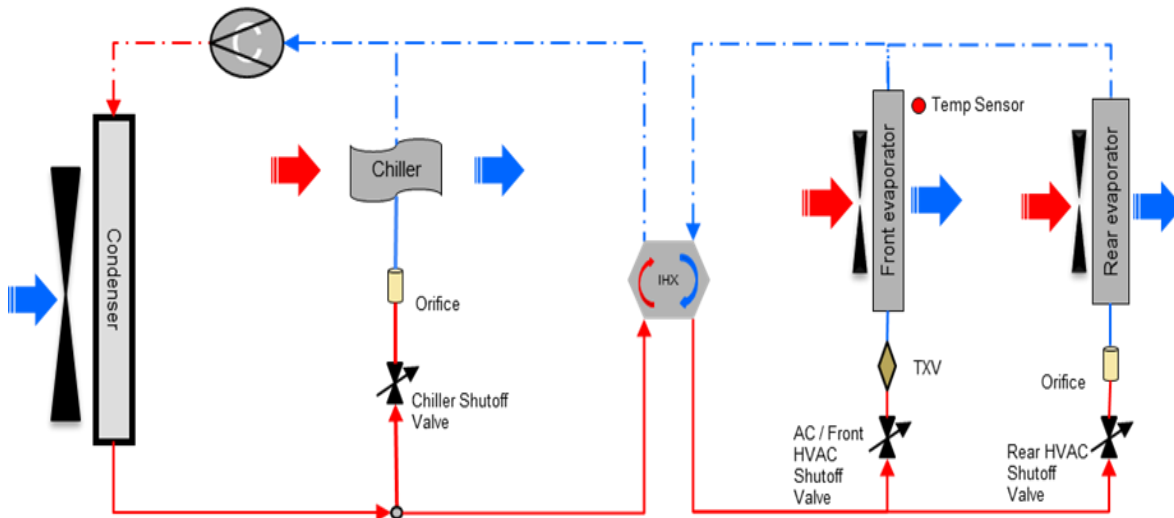
### **3.3.5 Air Conditioning A/C**

The A/C system in the hybrid cars is somewhat different from the A/C systems before, as along with the other requirements the cooling of the high voltage battery coolant via the heat exchanger BCU. When in pure driving mode the A/C in the passenger compartment is switched OFF and will be only used if the temperature exceeds the critical limit and battery needs the cooling [17]. There are three different operating conditions for A/C,

- Operating condition 1, Cooling the passenger compartment
- Operating condition 2, Cooling the passenger compartment and High-Voltage battery
- Operating condition 3, Cooling the High-Voltage Battery

## **3.4 Cooling System**

The cooling system (Cooling of the compartment) starts from the compressor which rotates at certain speed based on the input temperature from the user to compress the refrigerant. This compressed high pressure gas, high temperature gas is passed through the condenser where its temperature is reduced but the pressure is still not reduced. After that the refrigerant passes through the high pressure fill valve and after that there is a division. When the cooling of the battery is required the chiller shut off valve is switched ON.



**Figure 3-5 Air Conditioning Loop**

It is explained in the cooling of the battery section. The refrigerant now passes through the IHX which helps the cooling and increases the efficiency of the cooling of the refrigerant. After the IHX depending on the requirement from the user it either passes through front, rear or both HVACs. For the front HVAC after the shutoff valve is open, the refrigerant passes through the TXV where the pressure of the refrigerant is reduced [16]. (*When it passes through the front evaporator the air is blown through the evaporator to provide the cool air to the passenger compartment*). The refrigerant is now a low pressure low temperature gas which after passing through the IHX goes back to the compressor to complete the cycle. The compressor speed depends on the temperature set by the user, lower the temperature wanted by the user higher the compressor speed will be.

### 3.4.1 Compressor Module

This module is responsible for controlling the compressor and communicates with the ECM via HS-CAN. All the commands and requests are served and in case if there is a fault in the EL-A/C then the diagnostic trouble code is generated. The ECM receives the message about the fault and sends a signal via CAN to DIM, which shows the message to the driver about the need of the service of A/C.

### 3.4.2 Electric A/C Compressor

The Electric compressor has replaced the custom combustion engine's mechanical compressor and is located at the very same place. The Electric A/C compressor is 33cc with angular speed ranges from 800 to 8500 rpm and has a specified refrigerant (R134A) capacity of 920 ml, with a 3-phase 400 V synchronous motor with an output of 4.7 kW and is driven by the direct current (DC) from high-voltage battery of the car [18]. The DC is converted to 3-phase AC by the built in converter on the compressor for the compressor's electric motor.

### 3.5 Battery Cooling System

Cooling of the battery is an important job as the certain rise in temperature ends up in battery being inefficient and lessen of life time. So to get full use of battery the cooling of battery is important. It is controlled by ECM on the command of which the chiller in the cooling system loop activates and provides the cooling to the battery as shown in figure 3.2.

### 3.6 Heating System

The heating manager controls the heating of the passenger compartment and engine [17].it uses the heat of the coolant which is being heated by engine there is a separate loop for this system which is in contact with the engine cooling loop having the HVAC heater and is shown in figure 3.6,

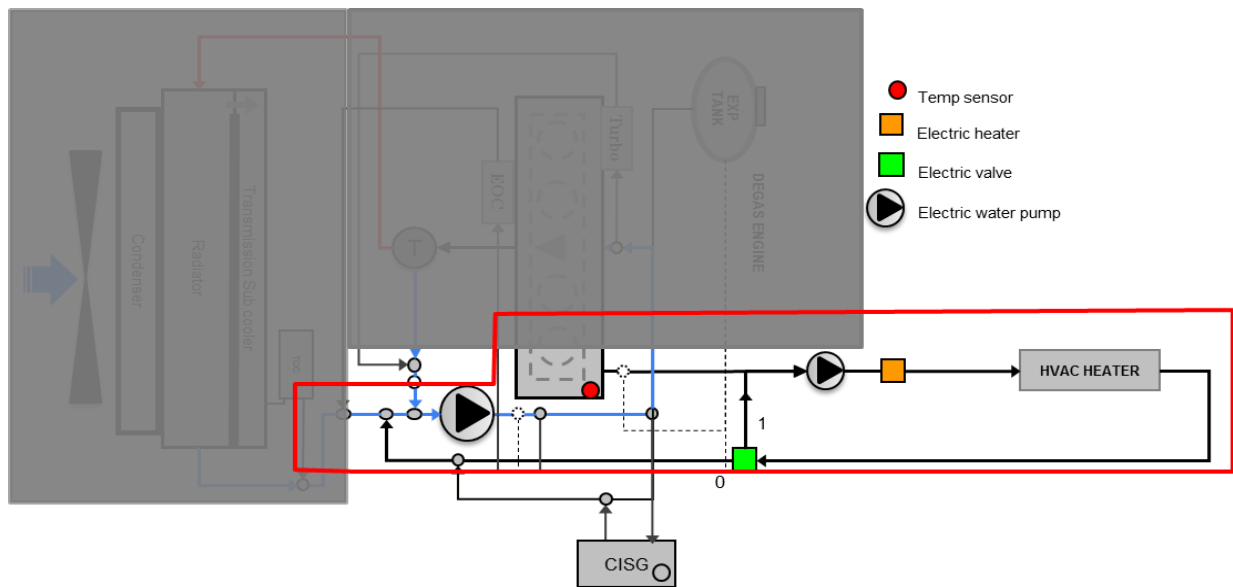


Figure 3-6 Heating system Loop (passenger compartment)

#### 3.6.1 Fuel operated heater (FOH)

FOH is available for both left and right-hand drive cars, it can only be activated when the ambient temperature is below a specified level and the operational time is limited.

#### 3.6.2 Restricted cooling coil FOH - passenger compartment element

FOH heats the engine before the engine block by a 3-way valve restricting cooling coil to the heater and passenger compartment element. When the target temperature is reached in the restricted coil, the valve closes the path to the restricted coil as the engine block is also heated by FOH.

#### 3.6.3 Electric heater for passenger compartment PTC

The passenger compartment heater is powered by 12V network of the car.

#### **3.6.4 Electric Engine Heater (optional)**

This heater is powered by the current from the electrical network and is supplied via OBC which is controlled from the preconditioning settings.

### **3.7 Climate Comfort in Hybrid Electric Vehicles**

The very first hybrid vehicle was introduced in market was in 1997 and after effort of more than 10 years, Hybrid vehicles have made in to 1% of the global market. Hybrid vehicles are powered by petrol, diesel and electric motor which are regulated by power storage battery. There is a wide range of different configurations for the hybrid electric vehicle depending upon the role played and capability of battery and electric motor, which includes Micro Hybrids, Mild Hybrid, Full Hybrid, Plugin Hybrid (PHEV), Series / Parallel Hybrids and Series-Parallel Hybrid [19].

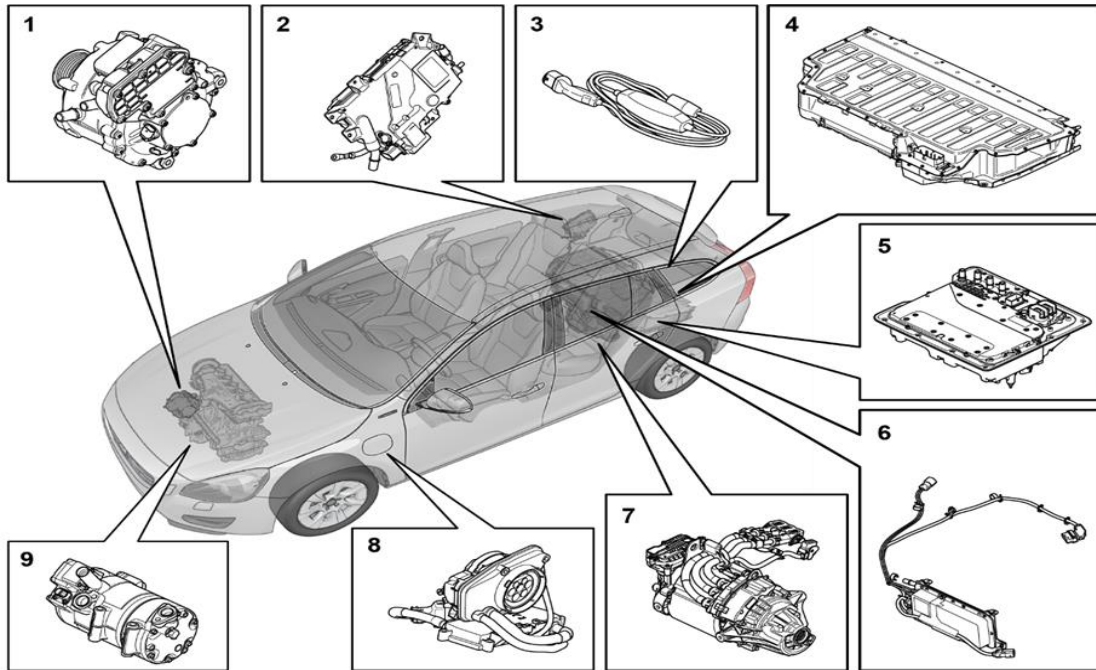
#### **3.7.1 Cooling/Heating system**

For air conditioning system the conventional belt driven compressor (with the fuel engine) is used and when the somehow engine is idle then a device called storage evaporator is used for cooling. In case of full hybrid vehicles, electric compressors are used to fulfil the cooling needs of passenger compartment. This definitely helps in preconditioning (cooling of passenger compartment before driving) of the compartment in harsh weather. As far as the heating of passenger compartment in cold weather is concerned, the waste heat from the engine is used. Also there are PTC heaters are used for preconditioning.

### **3.8 Electrical Architecture**

The electrical systems in Plug-in Hybrid are divided in to high voltage and 12 volts. The high-voltage section consists of both AC and DC, as battery stores DC whereas motors or generators work with 3 phase AC. The high voltage section has a voltage between 230 to 400 and is mainly used for hybrid operations and for driving the A/C compressor. For the purpose of control and signal the high-voltage components are also connected to 12 V circuit.

In the figure 3.7; 1 shows the ISG which is used for starting the internal engine and generating current for high voltage section. Number 2 shows the DCDC, which is a control module for DC to DC convertor as it converts the high voltage DC to 12V DC. 3 is the charging cable for setting the charge current. 4 is the High Voltage Battery for driving ERAD during the electric drive and other High Voltage components. 5 is the ISC which contains two separate voltage convertors IGM and IEM that convert between the high voltage battery's direct current and 3 Phase alternating current for the components. 6 shows the OBC is a charger which converts 230V AC mains power to 400V DC for charging the high voltage batter and operating the EL-A/C and DCDC during mains power recharging. 7 shows the ERAD is a 3 phase AC motor for electric and hybrid drive mounted directly on the real axel which also works as a generator with energy recovery during breaking. 8 shows the sharing socket which is a connection for 230V main power and 9 shows the EL-A/C which is an electric A/C compressor.



**Figure 3-7 High Voltage Components [16]**

# 4 OO-FMEA for Climate System

## 4.1 Introduction

OO-FMEA has been developed at Volvo Car Corporation specifically for analyzing complex automotive systems which are often built within huge electrical architecture where multiple ECU's interact and share software and hardware resources. Information transmission between components and information computation are extensive.

Performing FMEA on these systems is a great challenge because the individual sub-systems have overlaps and their boundaries are often indistinguishable and FMEA alone is not a good approach to cope with the complex systems.

The main problem with the complex systems is starting and the ending points, finding of which is never less of a challenge. This problem is solved with the help of OO-FMEA which also gives a full control over the targeted areas when prioritization of objects is done. The prioritization is done based on the communication between the design intents and their functions. In OO-FMEA logical objects are developed which are good to handle software as it is a good approach towards the software analysis. All the interactions must be identified which will help about the priorities of the analysis. OO-FMEA resolves these issues by applying an approach based on knowledge of complex systems behaviors and application of object-oriented analysis from the software development practices [2].

The OO-FMEA approach starts by finding simplicities in the complexness in order to master the system or sub-system under study, by identifying its structure and behavior. The system structure contains the system elements within an appropriately defined boundary, the operational environment and the shared resources. The system behaviors, basically the functional and not functional capabilities, are decomposed into separable physical, logical and attribute objects. OO-FMEA has been in use at the electrical and electronics systems engineering department at Volvo Car Corporation since 2006.

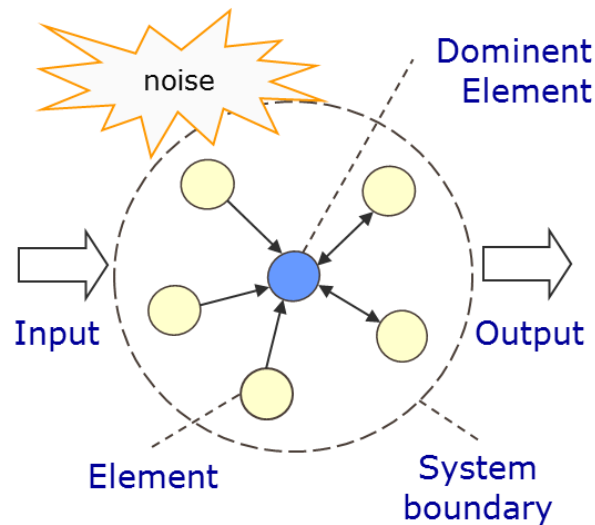
## 4.2 Simple and Complex Systems

A system is said to be simple when it has well defined inputs / outputs and its boundaries are clear. It has limited number of system elements which combine to make the system and there is one dominant element which co-ordinates with other elements. It has a well-defined system boundary as shown in the figure 4.1.

Whereas any system which is composed of various dependent and/or independent, densely interconnected components having multiple level of details is said to be a complex system. The complexity of such systems can be described by the interactions and interfaces between the components as well as other interacting systems based on their inputs and outputs. The inputs from these systems may unveil some properties due to certain interactions which can never be expected from the properties of the components. Complex systems may not have well defined inputs and outputs because the subsystems often overlap each other and share resources extensively. Generally a complex system contains both complicated and simple

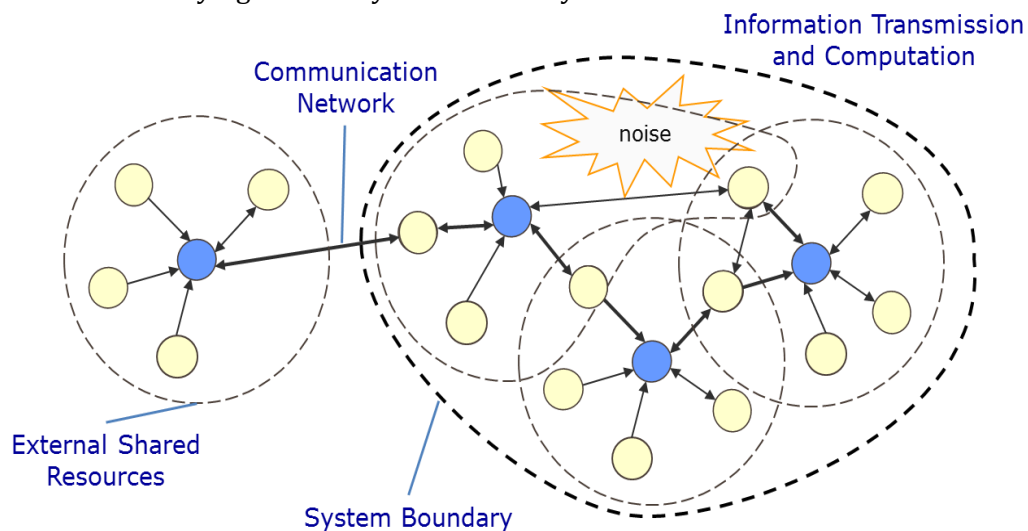


elements. The complicated elements perform the varying tasks, whereas simple elements perform highly repetitive tasks. [20]



**Figure 4-1 Example of simple system**

While the functions of simple system is always control by a dominant element e.g. a relay or other control unit, a complex system may have its control functions allocated in more than one ECU. In addition, a single ECU can be involved in controlling a few sub-systems. For example, apart from controlling the engine, the Engine ECU is also involved in controlling the cruise control system, the fuel system, the air condition system etc. Consequently, the importance of identifying the sub-system boundary cannot be underestimated.



**Figure 4-2 Example of complex system**

## 4.3 Sub-system Boundaries

### Types of Interface

The most significant factor to consider when identifying the sub-system boundary is the interface of the system element.

Interface is a point at which different elements connect or interact. When identifying a sub-system boundary in a complex operational environment where multiple systems are integrated, the nature of interface must be understood. At any interface point, the system elements assert an effect on each other. The type of interface decides what kind of affect the elements or the processes have on each other. When a two way effect occurs with a feedback, the connecting elements in fact interact with each other. This distinction of an interaction to a simple interface is an important aspect in identifying sub-system boundaries. Since data transmission is a significant process in complex automotive system, the interfaces can be categorized according to the method of communication [2].

#### Data transmission without feedback (Simple Interface)

In this type of interface, data is transmitted from one entity to another without any feedback between the connected entities. The transfer of data can be one or two ways, but is independent of each other. At the system level the data can be regarded as input or output.

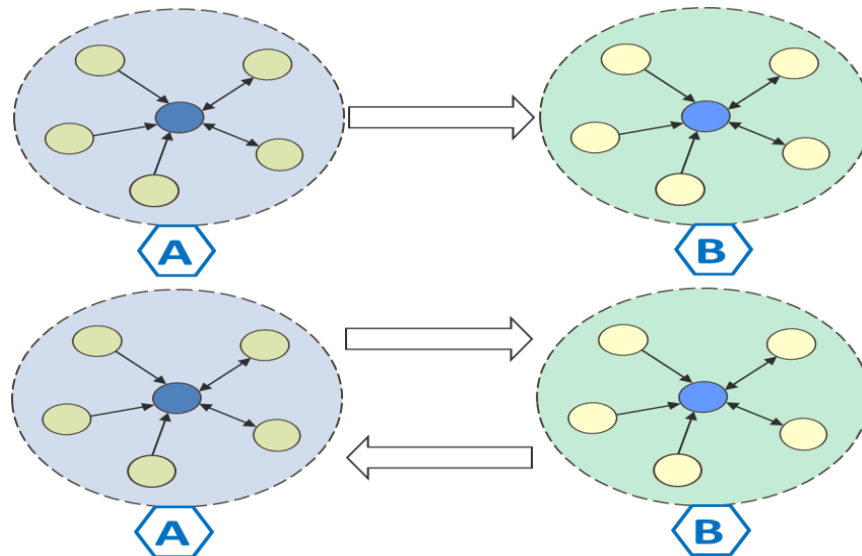
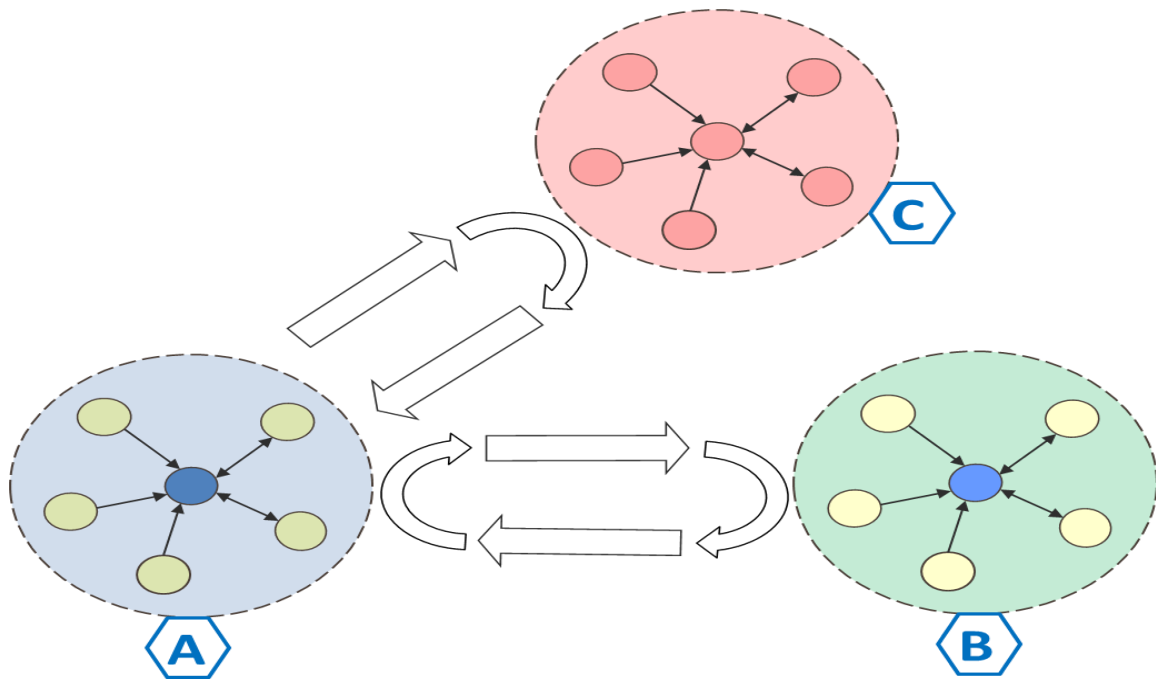


Figure 4-3 The Interface between two processes

#### Data transmission with feedback (Interaction)

Interaction is a type of interface with interdependent two-way effect. In other words, interaction is a two-way communication with a dependent reply of data from the recipient, which is the only difference that makes it important enough to include it in the sub-system boundary. The feedback can be single or multiple, or in other words the sender can also be the recipient of data to qualify for interaction. For example interaction is when some input

given to the system, system sends out in response to that input and based on the output, some more input is given to the system. The presence of interaction with the system is one of the criteria for deciding if an element belongs to a sub-system [2].



**Figure 4-4 Interaction between multiple processes**

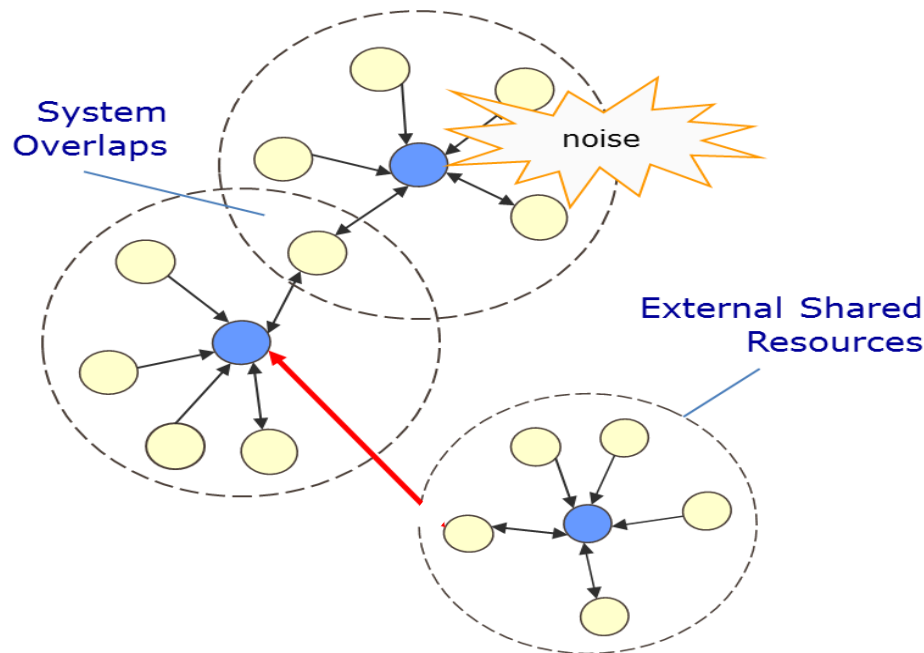
#### **Criteria for inclusion in a sub-system boundary**

The other criterion for deciding inclusion in a sub-system is whether the element is unique or not. A sub-system boundary encloses all the elements that interact with one another and the elements that are unique to the system. A user can be considered as the elements of the system, when the user responds to system based on the output from the system, because the user interacts with the system. For any element to be included in the system it must satisfy at least one of the criteria,

- The element interacts with other element in the system
- The element is unique to the system

#### **External Shared Resources**

The elements outside the sub-system boundary are also being used by the sub-system. Basically these components do not “interact”, with each other but do provide vital information for the system in the form of input from other sub-system and if these components are not considered, they can be cause of certain failure modes. The interface between the system and external shared resources must be captured in the design intents of the objects.

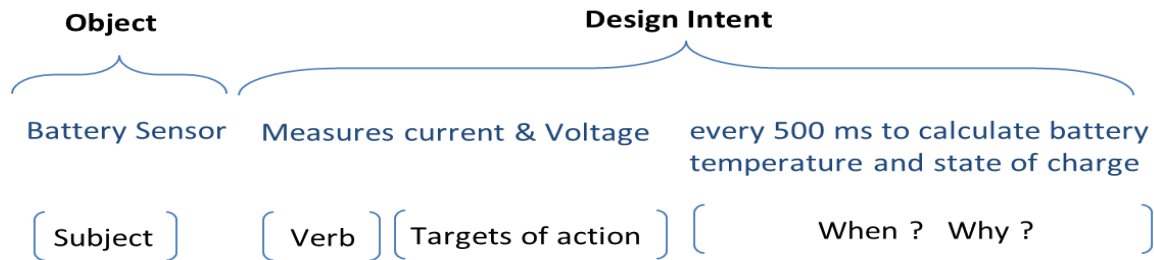


**Figure 4-5 System Overlap and External Shared Resources**

### **Object and design intent**

An object is an information package containing a name and brief, but accurate description of the design intent of a separable part of the system. There are three types of objects, which are physical, attribute and logical objects. The design intent of an object basically shows the perception about the working of the object in the system, it explains what does this object do and what is its purpose. The motivations for all its actions can also be included to enhance the effect identification. As design intent contains the information, which must answer the questions, such as, what the object does, where and why it is applicable. Identification of the objects and their design intents is done from the borders of the system boundary. There are some rules which are taken under consideration when defining the design intents, and these rules are as follows,

The design intent is basically composed of a verb in the start which shows the function of the object, then in next part of the design intent, it has the targets of action, what would it achieve, and in the last part it has, when would it be done and why would it be done. For example,



**Figure 4-6 Difference between Object and Design Intent and elements of Design Intent**

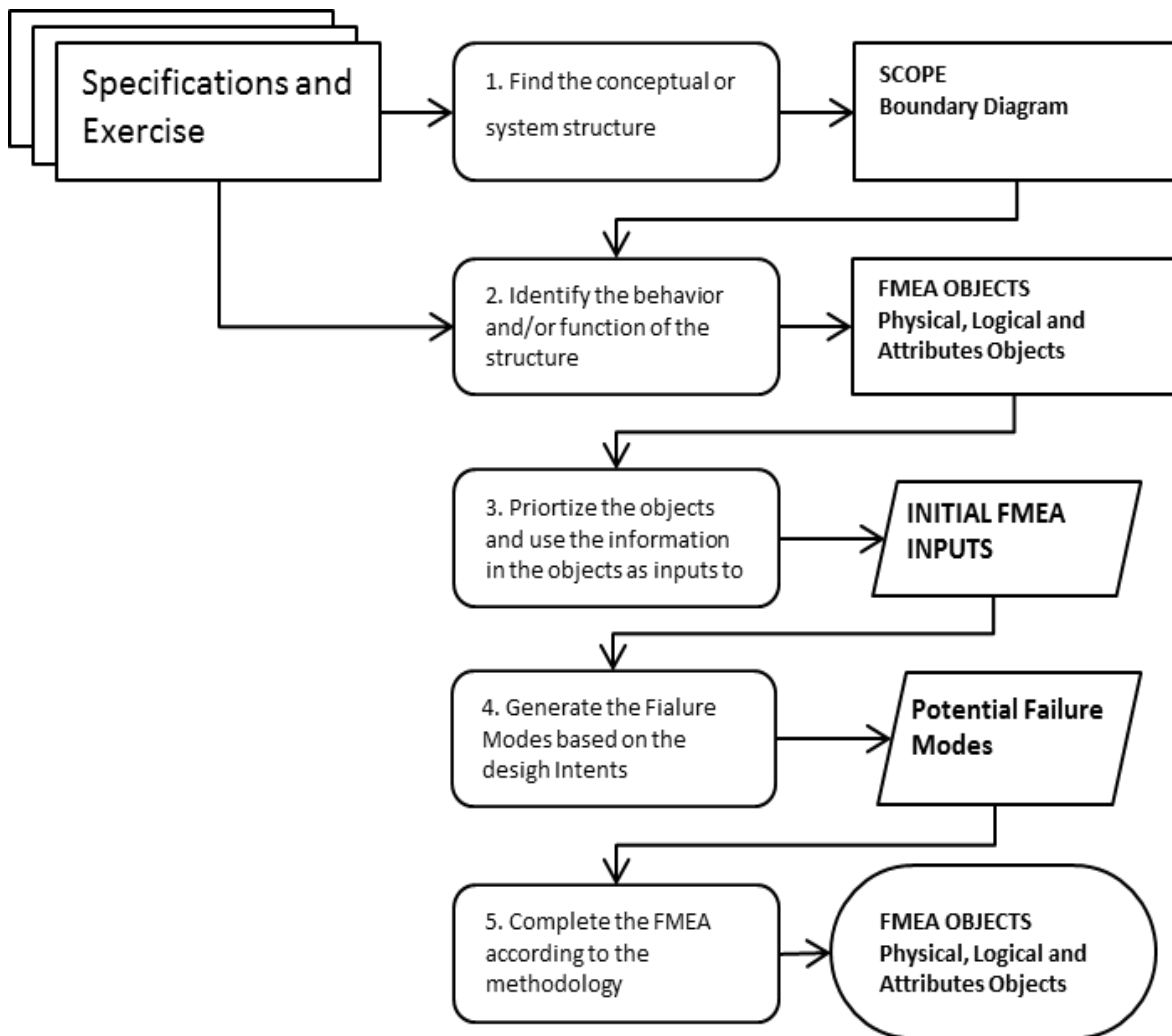
#### **4.4 Comparison between tradition and object oriented FMEAs**

Traditional FMEA is very less capable of analyzing the complex systems, degree of relevance not apparent having too small or too large scope with no defined approach for software. Having no specified starting or ending point therefore traditional FMEA has not done any adaptation for modern process [10]. Though traditional FMEA is applicable and easy to implement on the simple system but as far as complex system are concerned, Object Oriented Failure Modes and Effects Analysis (OO-FMEA) is the tool we are talking about [9]. As the name shows it is object oriented, decodes the complexity and do the qualitative analysis [12]. It focuses on the design intentions which ensure the high degree of relevance. By degree of relevance it is meant here is sometimes when traditional FMEA is performed it does not cover all the relevant aspects of the system which are taken under consideration and in that case it is said to have a lower degree of relevance and OO-FMEA has the high degree of relevance. Well defined system boundaries are optimized by defined criteria, to handle software there are logical objects, and when prioritization is done then it gives the full control over, and focus on the targeted areas. It identifies the incomplete design at the input stage which improves and simplifies the requirements and specifications. The objects made can be reuse and can be updated easily. OO-FMEA reduces the product development time and contributes to better prototype and testing.

OO-FMEA is an effective systematic process for identifying and analyzing complex potential designs of automotive system, ambiguous designs, incomplete structures and process failures (*with the intention to eradicate or to lessen the risk linked to them*). These failure modes often occur in extensive architectures, where linked components interact and share abundant software and hardware resources.

OO-FMEA resolves these issues by identifying its structure showing an appropriate boundary, its behaviors the operational environment and the shared resources; and then decomposes its functions and behaviors into separable physical, attributes and logical objects. Special attention is given to the Design Intentions (Design Intents) of every object in order to enhance the failure mode identification later on. These objects are then theoretically assessed, according to the logical reasoning of FMEA methodology. The object oriented approach conforms to the objectives of modern product development processes and lean principles. Following is the flow chart for the OO-FMEA process which shows how the process should be completed step by step. The advantage of this is that when some addition or

deletion of any process is required then it would easily be detected and its connection and dependencies (interaction) would be known.



**Figure 4-7 OO-FMEA Flow Chart**

OO-FMEA is an approach which makes comparatively much easier to analyze the complex auto-motive systems and sub systems that are built in extensive electrical architecture. The systems, sub systems components perform their task while being interacted, linked or even independent. To handle a complex system is a hard and tedious job. The traditional FMEA approach may easily be performed on the simple or less complex systems but on complex systems it is very hard to do so. That is why, after going through different processes the OO-FMEA is completed. There are 5 different steps which are performed, in order to complete the OO-FMEA on any system.

When doing the traditional FMEA on any system the following steps are taken under consideration.

- Identification of equipment or sub system and mode of operation

- Identification of potential failure modes and their causes
- Evaluation of effects on the system with respect to each failure mode
- Identification of the recommendation for reducing or elimination of any error or Failure Mode
- Testing (if possible)

When it comes to the procedure of performance of OO-FMEA on the system the following procedure are done [9],

- Identification or finding of the conceptual system structure and the boundary
- Identification of the objects and their behavior
- Prioritization of the objects which are to be selected for FMEA process and their addition in the FMEA template
- Generating the failure Modes based on the design Intents
- Completion of FMEA according to the FMEA methodology

Though the OO-FMEA process is longer than the Traditional approach but it is very much useful in certain ways i.e.

- OO-FMEA is much more feasible to handle the complex system
- It is very much useful in the detection of the incomplete designs
- Requirements which are unclear are identified and corrected
- Considering the design intents helps finding the interaction and interfaces which helps in location the system boundary
- In OO-FMEA the objects can be reused
- It saves a lot of engineering time
- It helps to have structure through objects for complex system analysis

The Object Oriented FMEA approach begins and concludes with the requirement description and specifications in every iterative loop and it is best described in the figure 4.8,

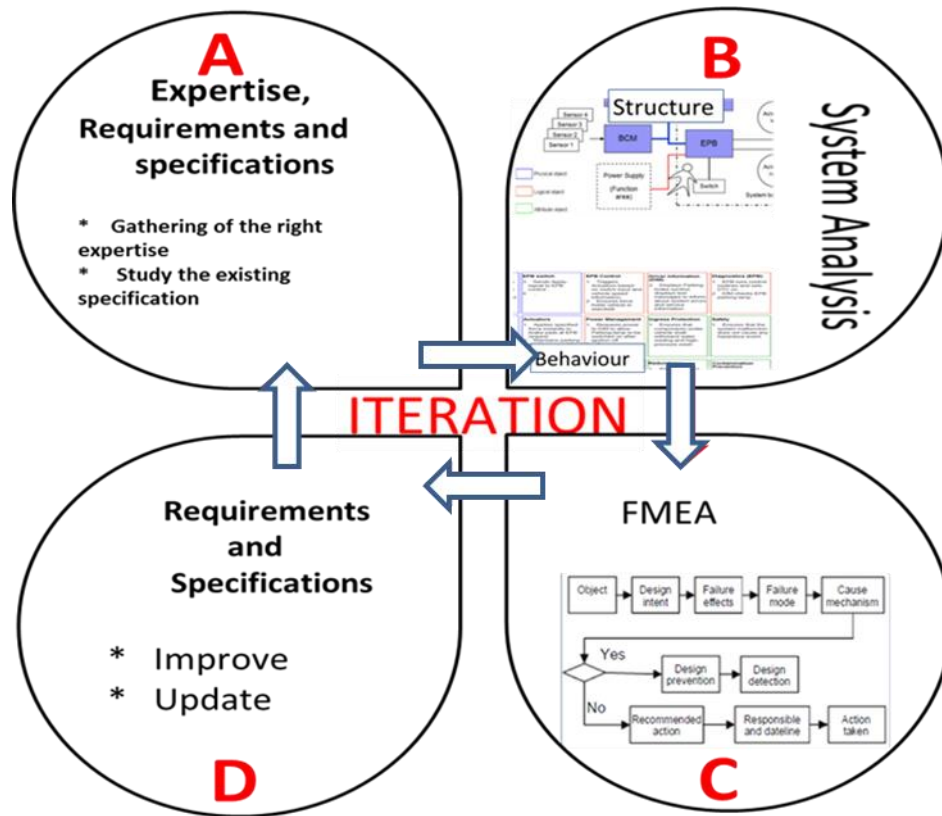


Figure 4-8 Working procedure of OO-FMEA

## 4.5 Implementation of OO-FMEA on Climate System

The Climate System is the maintaining of the desired climate set by the user based on the ambient conditions in the passenger compartment. The Climate System is composed of the Climate System module which has its communications with the other modules to have a maintained climate comfort.

### 4.5.1 OO-FMEA 1<sup>st</sup> step (Conceptual System Structure)

As mentioned in the earlier chapters about the OO-FMEA, this technique is applied on the Climate System. First of all, all the components which are participating in the Climate System are identified and considered. The first step of the OO-FMEA is to find a structure and make a prominent boundary. That information is taken from the SRD's System Requirement Description (Company's Documentation) and the electrical architecture document. This contains all the architectures, the allocation of the components and their connection, deployment of the components and their connections and all the basic details. Based on that data the schematic diagrams are made with all the possible and necessary components, sensors and actuators are shown.

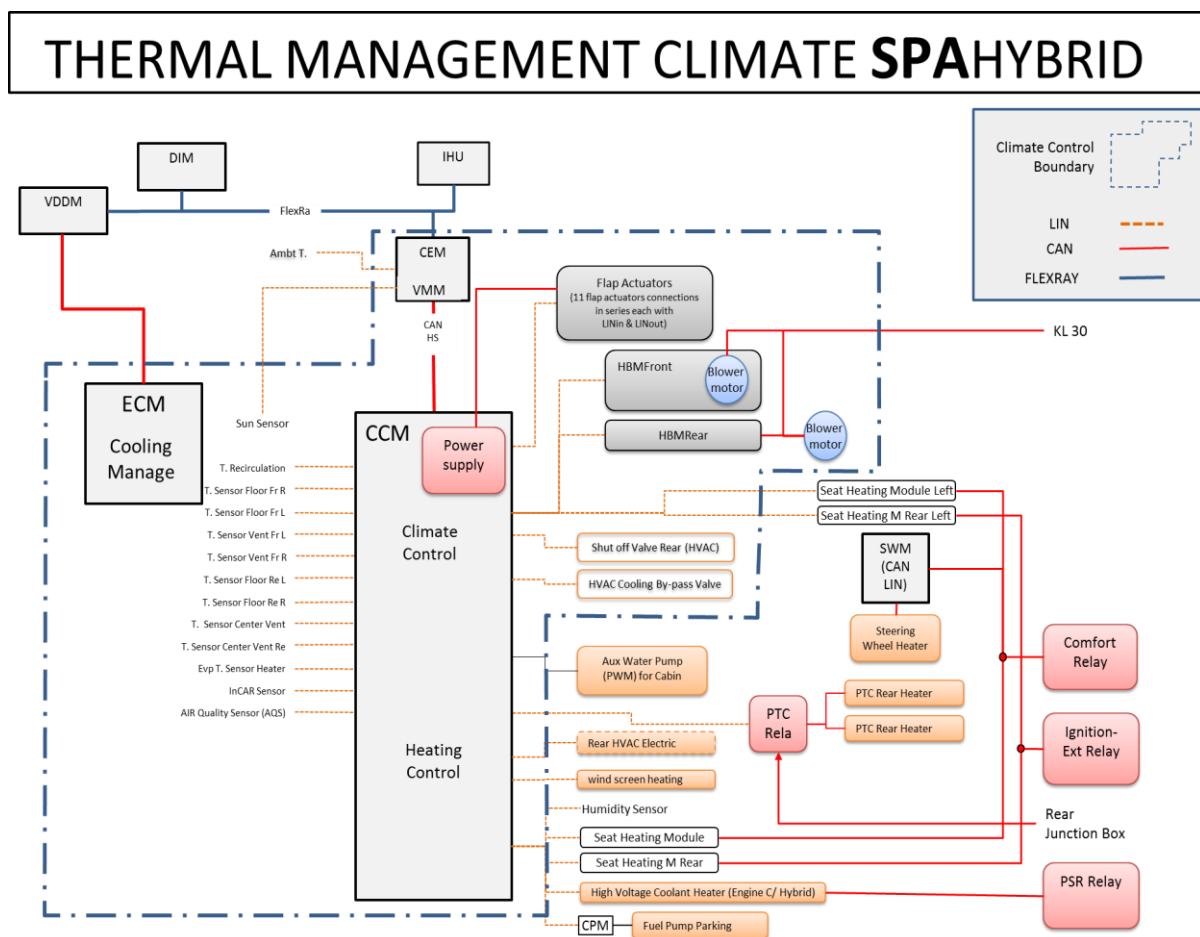
As mentioned earlier the components are included in the system boundary is based on interaction or uniqueness of the component. For the Climate System the boundary is made based on the interaction of all the components sensors and actuators participating in maintaining the climate comfort. The main module is Climate System Module (CCM) in which



all the calculations are taking place and all the controlling is done. Looking in to the criteria of including the components in to the boundary the components are added and the end result can be seen in figure 4.9,

## Climate System

In the diagram below the thermal management of the Climate System is shown with a dotted blue boundary line which shows, the components included in the Climate System. In this case the Climate System for heating is excluded from the boundary so that the Climate System should be subdivided into two parts to cope with the problems in a more efficient manner. As from the figure 4.9 it can clearly be seen that there is a main block of the Climate System module to which are connected all the sensors except for the sun sensor and ambient temperature sensor, which are connected to the Central Electric Module CEM.



**Figure 4-9 Block diagram of Climate System**

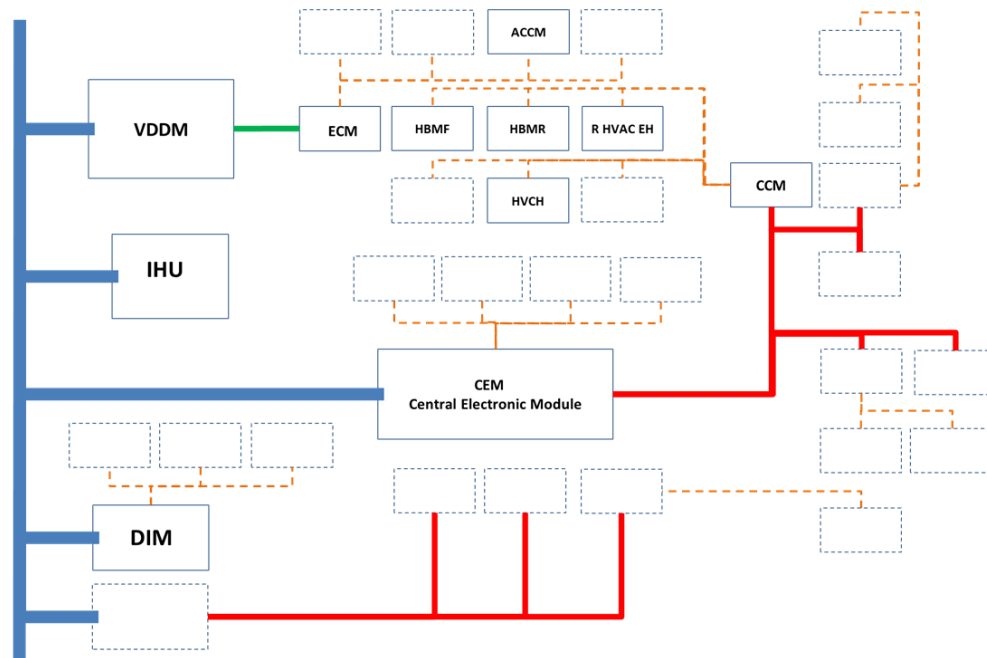
Climate System module takes the information of the ambient temperature from CEM connected via high speed CAN. All the Flap actuators which are responsible for directing the air in the air vents based on the climate comfort. The blower module is also connected to the Climate System Module. As seen from the figure 4.9 the data communication is done through

the CAN, LIN and Flex Ray, CAN is represented by a bold red line, Flex Ray is represented by the bold Blue line and LIN is represented by the orange dotted lines.

The black bold lines connected to the sensors are the Engine Control Module (ECM) is also shown within the boundary line as there is major interaction between these two when it comes to the requirement of the compressor for cooling. The A\C Compressor Control module controls the compressor and all the commands come from the Climate System Module.

## Topology

When modules and units are arranged on the network geometrically, the term used for that is “Topology”. The arrangement can be of different setting depending upon the requirement and the best performance, such as ring topology, star topology tree topology etc., [21] connections are made according to the requirement and best performance and is based on the use of buses such as LIN, CAN and FlexRay.



**Figure 4-10 Network Topology of the allocation of the modules**

## LIN

LIN is single wired low cost, low speed having a data rate of up to 20 Kbps asynchronous bus used in the products for non-critical applications. In the diagram it is represented with the dotted light brown line. LIN is used in master slave network [22]. In Climate System as mentioned graphically all the sensors which are connected to Climate System Module (CCM) including the Ambient temperature sensor and sun sensor which are connected to the Central

Electronic Module are connected through LIN. as far as the question of Actuators is concerned HVAC Blower Module (HBM) front and rear, Flap Actuators shut Off Valves are connected through LIN [23]. In the Climate System Diagram it is denoted by thin light brown dotted line.

## **CAN**

CAN uses unshielded two wire line, medium speed a synchronous bus having a data speed of 1 Mbps a medium speed asynchronous bus offering a data rate up to 1 Mbps [22] . In the diagram it is represented with a bold Red line. It is used in the combination of multiple master based architecture. CAN uses a data frame having a maximum payload of 8 bytes to transmit data [23]. In Climate System when it comes to the communication between the modules which contain many system and sub-system in them, CAN is used. As it is for multiple master based architecture therefor many sets of instruction would be flowing through it at a time.

## **Flex Ray**

When it comes to the safety critical applications in vehicles FlexRay is used. In the diagram it is represented with a bold Blue line. It is a serial communication and uses two channels, both of these channels have pairs of wires, and it has the data transfer rate up to 20 Mbps and it has a payload consist of 0 to 254 bytes for the transfer of data [23]. Each channel may be operated at the same time i.e. sharing the 20 Mbps in to 10 Mbps each and is used in different topologies, such as bus, star etc. In Climate System the main units are connected through FlexRay such as, Internal Head Unit (IHU) and Driver Information Module (DIM).

### **4.5.2 OO-FMEA 2<sup>nd</sup> step (Identification of Behavior)**

The second step when performing OO-FMEA is the identification of behavior of the system. Structure without behavior is useless if talking about any electro-mechanical system or any other system in which the user expects some kind of output. The first step of OO-FMEA is in which the structure of system is identified. To have a deeper knowledge about the system, its behavior has its own importance. If the behavior is defined in a simplest way it is, the how, when, why, where and with the help of which component the system performs any task. Obviously the completion of any task may require a set of instructions and actuators to have a desired output. The identification of objects and their design intents, and the information about these objects and design intents comes from the same source of course, the SRD's in which the description of the signals responsible to complete different jobs and perform different function.

The behavior is basically composed of three types of objects, which are based on the information from the SRD's. These objects are

1. Logical Objects
2. Physical Objects
3. Attributes Objects

## **Logical Objects**

The Logical Objects are shown in red squares and are software based which are responsible to perform different tasks, taking different decisions to have the operations performed according to the requirements set by the user and instruction from the Climate System for the required/set climate comfort in the passenger compartment. Logical objects are an information package containing the name and design intent of a separable part of the software. The design intents should be started with verbs so as to clearly describe the main function and other dependencies (if any) [2]. These function can also be realize by the combination of software and hardware e.g. Load management, electrical motor control, thermal management etc. Logical objects represent a separable behavior or function at concept level and are software models at system or component level.

## **Physical Objects**

The Physical objects are shown in blue squares which represent the hardware or tangible devices which take part in the completion of any process [2]. It is an information package containing the name and design intent of a separable hardware or tangible (flexible) element in the system e.g. electric control unit, relay, switch or sensor etc.

## **Attributes Objects**

The attributes objects are represented with green square, which define the attributes of the design intents of the logical and physical objects [2]. Basically the attributes objects holds the desired conditions and quality level of system, subsystem or to which it refers to. In case of vehicles it would include the design intents such as, legal requirements, crash Handling, passenger's protection, system performance, prevention against noise factors etc. for a system or a product to have good quality the quality history of that system can also be taken as the attribute object. When software is written the information in the attributes objects are considered important because it tell what are the factors must be taken care of by this software. The attribute object is intangible and it is not independent, these are to be implemented by other logical objects. For example what are the processes should be activated in case of crash, the noise should be taken under consideration and should be reduced when used the compressor at high compressor speeds, and the response time of different parameters should be taken under consideration and should be according to the set standards.

<b>RECIRCULATION</b> 44. Sets the recirculation (REC) to maximum and out side Air (OSA) to minimum when AQS... 151. Performs 100% recirculation while activating manually, unless some other function ... 36. Defines the recirculation degree as a result of the actual degree of recirculation of .... 123. Requests a calibratable degr.....	<b>Air distribution . . . .</b> 1a. <b>Sets desired values for defined parameters to have air distribution same in all the ...</b> 1b. Maintains the relative air distribution (defroster/floor/vent) in ... 2. Distributes auto normal air flow and.... b.Pre-conditioning is activated and deactivating pre conditioning returns the settings to the last one... 3. Distributes a small amount of air (through floor) to the second seat row when climate ...	<b>CoolantValve</b> 1. Control the coolant flow through HVAC heater	<b>HVCH</b> 1. Adds heat in the coolant via electrical current, high voltage 2- Controls the temp. to avoid abnormal operation 3- Regulates power usage based on measured voltage
<b>Air flow (wanted, requested, calibrated, set, calculated, selected - Difference?)</b> 1. Quickly achieve and maintain climate comfort and good visibility in an ECC-System by selecting a total and defroster air flows .... 2. Sets blower settings based on HMI requests MAX, auto++, auto+, auto,.... 3. Reduces the total air flow as a function of ambient temperature when decreasing the defroster air flow, if the defroster air flow is limited due to condensation ... 4. Lowers the total air flow from the main HVAC if the available heat is low in order not to drain the heat ... 8. Sets the total air flow (LoLo\HiHi) to a high calibratable level which is used in autonormal fan.... 9. Adjusts the air flow due to the lack of cool and dry air when A/C OFF. the level of....	<b>Defroster</b> 1. Choses a separate calibratable ambient temperature dependent head level setpoint (typically few degree above the highest normal setpoint) for the first seat row when max defroster is selected. and if the customer changes tempset the normal head temperature setpoint should be used. On turning OFF, tempset returns to the setting when max defroster was activated. C 2. Calibrates the air flow at constant levels, irrespective of the ambient temperature and control error etc as long as Max defroster is active and on exiting Max defroster the air level will return to auto air flow levels as before the Max Defroster. C 3. Lowers defroster air flow with same percentage as the first seat total air flow, maintaining the relative air distribution defroster/floor/vent for the first seat row, if the total air flow is lowered due to low vehicle speed. 4. Change the wanted head temperature for the first seat row when defroster airflow is deviated from the base defroster airflow like at mistrisk, AC ON/OFF. Change should be calibratable and depend on ambient temperature and magnitude of the defroster air flow.	<b>Crash handling</b> 1- Shut down the blower at crash 2- Shut down the fuel operated additional heater at crash	<b>Noise Perception</b> Ensures perceived sound from the compressor, blowers, actuators and flap movement do not irritate the passengers.

**Figure 4-11 Examples of the logical, Attributes and Physical objects**

### **Defroster (Case Study)**

When talking about Climate System the main goal is to maintain the climate comfort according to the requirement from the user, instructions from Climate System unit and is based on different parameters such as, ambient temperature, Humidity, sun load etc. In Climate System, comfort also includes the action taken in response to different processes affecting the climate in passenger compartment. The factors like the activation of Defroster when required. Though the importance of defroster can never be denied but at the same time with its activation there is an abrupt change in the climate of the passenger compartment and the Climate System acts accordingly using different set of instruction and with the activation and deactivation of different processes.

Defroster is used to dehumidify the windscreen when the humidity in the passenger compartment reaches the dew point which cases the mist on the screen occurs. "The temperature below which the water vapors (in the air at constant pressure) condense in to liquid to form dew is called as **Dew Point**" [24]. Defroster is basically the air from outside being blown directly on the wind screen and on the side windows so that the mist should be removed so that the visual problem should not occur to the driver. This is a manual function which is activated when the driver feels the need of it. So when the defroster is turned ON definitely, the air coming from outside (which is relatively cold air) will affect the climate, so the Climate System will act accordingly and as long as the defroster is ON the flow of warm air from the driver and passenger air vents will also be made increased by the Climate System to maintain the climate comfort.

### **Defroster**

1. Choses a separate calibratable ambient temperature dependent head level setpoint (typically few degree above the highest normal setpoint) for the first seat row when max defroster is selected. and if the customer changes tempset the normal head temperature setpoint should be used. On turning OFF, tempset returns to the setting when max defroster was activated. C
2. Calibrates the air flow at constant levels, irrespective of the ambient temperature and control error etc as long as Max defroster is active and on exiting Max defroster the air level will return to auto air flow levels as before the Max Defroster. C
3. Lowers defroster air flow with same percentage as the first seat total air flow, maintaining the relative air distribution defroster/floor/vent for the first seat row, if the total air flow is lowered due to low vehicle speed.
4. Change the wanted head temperature for the first seat row when defroster airflow is deviated from the base defroster airflow like at mistrisk, AC ON/OFF. Change should be calibratable and depend on ambient temperature and magnitude of the defroster air flow.

**Figure 4-12 Defroster the Logical Object**

In the defroster logical object shown in figure 4.12 there are four design intents which take part directly in the use of defroster when it is needed and changes are taken place accordingly. These design Intents are explained in detail below respectively,

1. Explanation: - When there is mist on the screen the user turns ON defroster to have the mist reduced. When the defroster is turned ON there are many other parameters which are taken under consideration, i.e. when the defroster is turned ON the Head Level temperature which is dependent on the ambient temperature is calibrated with the change in the passenger cabin due to defroster. In other words the defroster is a function which sends in the air from outside when there is mist and when the outside air enters the compartment there is definitely a change in temperature taking place. So when the defroster is turned ON a separate calibratable ambient temperature dependent head level set point which is a few degrees above the highest normal set point, is selected for the first seat row (Driver and passenger seat). And if the customer makes some changes in the temperature (when the defroster is ON) then the normal head temperature set point (set point is the temperature set by the user) is used. And when the defroster is turned OFF then the temperature returns to the setting when the max defroster (Defroster) was activated.

2. Explanation: - The air flow is also dependent and is calibrated according to the ambient temperature conditions. And for the defroster to work fine and efficiently the air flow blown out of the defroster vent should be at high speed, and when the Max Defroster (Defroster) is turned ON it is obvious that there is a decrease in the total air flow In the air vents (Vents for passengers) this is the control error and is then under consideration by sending the total increased air flow from the air vents so as to fulfill the requirements without any decreased or less efficient function of affecting the passengers. As long as the max Defroster remains ON the increased supply of air is made sure and when the defroster is

turned OFF the air flow level is reduced and is set to the point where it was before (before the defroster was turned ON).

3. Explanation: -The air flow is calibrated with the speed of the vehicle, when the vehicle is moving at slow speed there will be a relative low speed as compared to the vehicle at high speed. So when the Defroster is ON and there is a variation in the speed of the vehicle, this variation would also effect with the same percentage on the air flow in the defroster, air flow in the floors and in the vents of the first and second seat rows.

4. Explanation: -The Defroster is operated at different levels depending on the level of mist in the wind screen and for that the mist is calculated based of the calculations/measurements of the wind screen temperature and level of humidity. If the level of humidity reaches the dew point (that point at which the dew) and the delta dew point is also calculated with the help of humidity sensor. Perform demisting by increasing the defroster airflow according to the demand of demisting based on the calculated mist risk (Humidity sensor) and (ambient temperature). The following relation is of great importance.

$$\text{Dew point} = \text{wind Screen Temperature} - \text{Delta Dew Point}$$

These above are the design intents which show the defroster function and the changes which are made accordingly when defroster is turned ON and OFF. The above is shown how the design intents are used to describe the functionality of the objects. Explain and derive the relations of dew points.

#### **4.5.3 OO-FMEA 3<sup>rd</sup> Step (Prioritization)**

The prioritization of the objects is one of the most important tasks which should be performed in an efficient way to that the work load should be lessened this is the actual relief in OO-FMEA. It deeds the principle of efficient compatibility rather than unmotivated completeness. In other words the analysis targets on the significant issues. Due to the interactions between the objects, the high priority will include the effect of the low priority objects. After the prioritization simply transfer the information in to the objects to the FMEA-template. The objects are prioritized and the information the objects is used as inputs to the FMEA. The idea behind the prioritization is to select the most important and main objects which have most interactions with other objects, no matter where the deployment of the object is. The interaction between the objects shows the root importance of the objects. When the objects are being prioritized, things which should be taken under consideration are the number of interactions. Prioritization also applies the working principles of complex systems, some objects have highly complex behaviors and they require high attention, while others have highly repetitive behaviors and may be treated with lower priority. The analysis of the objects can distribute to different groups so that parallel analysis teams can performed.

When the finding the behavior of the objects is concerned in the step two of OO-FMEA process then there are many objects and all the objects are combined to represent a system. Each object has its own function. But when the consideration of the object in the system boundary is concerned then at that time interactions between the logical objects and the

uniqueness of the logical objects make the system boundary. If the object is having no interaction at all is termed as a unique object and it is included in the system. When in a system any object is sending out some output to other objects in different modules that may not be of that importance because it is not affecting the system's output. In my project of OO-FMEA on Climate System, after the step of defining the system boundary and determining the behavior, there are a number of logical objects which makes it quite hard and time consuming if the FMEA is done on all of the logical objects and it is the beauty of the OO-FMEA approach it makes it possible to prioritize the objects to be considered for FMEA step which makes the job done in quite a short time comparatively. Reused objects that are derived from stable standard components regulated by proven design guidelines can be exempt from transfer to the FMEA, if their design intents and operational environments are not enough. The numbers of objects which are prioritized are shown in table 1.

Below is the list of all the logical objects which are participating in the Climate System. The first six logical objects which are bold to make these objects prominent are taken under consideration to perform FMEA because these first six logical objects cover almost all the other logical objects. Below are mentioned in the tables logical, Physical and Attributes Objects which are present in the Climate System.

<b><i>Logical Objects</i></b>	<b><i>Logical Objects</i></b>
<b>Climate System</b>	System Start-up and Shut-Down
<b>Air Distribution</b>	Evaporator Valve If Rear
<b>Air Flow (Requested, Calibrated, set, Calculated, Selected)</b>	<b>Air Flow (Adjustment for first, second and third seat row)</b>
Compartment Temperature If Front	Start / Stop
<b>*Defroster</b>	Limp Home
<b>Demisting</b>	Electrical Load Control
Anti-Flash Fog	Flap Manoeuvring
Air Recirculation	HVAC Flap Control Front
ECU for Climate Mode Manager	Parking Climate
Car Configuration manager for Climate System	Air Quality Sensor
Sun Load	HVAC blower If Front
Humidity Sensor	HVAC blower If Rear

**Figure 4-13 List of logical objects**



<i>Physical Objects</i>	<i>Physical Objects</i>
LIN	RHVAC Heater
Flex Ray	TEM
Cable Harness	Power Logics
AUX Water Pump	Flap Actuators
Flap Actuators	Temp Sensors
Air Quality Sensor (AQS)	Sun Sensors
Central Electronic Module	CPM
INCAR Sensor	HVAC blower Module F
HV Coolant Heater	HVAC blower Module R
Coolant Calve	IHU
TXV rear VAC	

**Figure 4-14 List of Physical Objects**

<i>Attributes Objects</i>	
Noise Perception	Legal Requirements
Assembly and Service	Crash Handling
Forced Cooling	EMC
Diagnostics	Responsiveness

**Figure 4-15 Attributes Objects**

#### 4.5.4 OO-FMEA 4<sup>th</sup> Step (Generating the Failure Modes)

Traditional FMEA is a design tool, a systematic process used to identify failures before their occurrence. This is done with the plan, intention to minimize and eliminate these failures and the risks associated with them [11]. It is a design tool which is recognized as an important and essential function in design and concept for the development of any electro-mechanical system [2]. The basic need of FMEA comes in mind when any system meets to the worst failures or deviations which could have been avoided if the use of FMEA made possible. It does not totally eliminate the errors or failures but it points out the failures along with the recommendations and the decisions regarding the elimination or minimization of the failures or the implementation of the recommendations is taken by the owner of the system and the design team involved in the FMEA process.

The FMEA has a structured report to have findings outlined which are developed from FMEA work sheets. The main reason behind those findings is to concentrate on the failure modes found, which would affect the system sooner or later. The FMEA results in to recommendations to improve the design which are seriously taken under consideration to have the failures reduced or the product upgrade. For any system or product FMEA becomes essential when it is to be used under such conditions where chances of failure modes to occur are greater.

In the FMEA process there are many types of failure modes which are being learnt, found which affects the system in different ways. If these failure modes are left undetected could affect the system badly may result into total destruction. As the FMEA process is documented at every bits and piece level so when an unacceptable failure mode is identified, the report or documentation regarding the failure mode should be forwarded to the designer so that it could be taken care of at the design phase [25]. But if something goes undetected, it may be noticeable to the clients. So before that happens it must be detected in the design phase and should be well taken care off. Whenever the FMEA is concluded the solution is explained and discussed with the design team and owner. According to the requirements from the owner, the owner is told about the results and what kind of changes and up gradation may be required to have a system with less errors, and if the changes in the existing design are required then it depends on the owner whether he wants to change it or not. If it is the matter of small changes which lead to greater good then this is discussed with the design team and the decisions are taken.

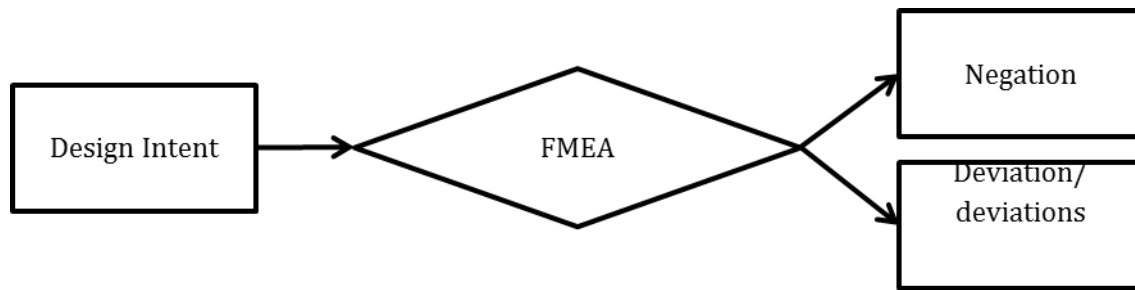
When it comes to the up gradation of the existing product then in that case the previous model is analyzed and on the basis of the results from the previous product, decisions regarding the new product are very easy to consider. In traditional approach of FMEA, it was very difficult to upgrade the existing product, to overcome that problem the OO-FMEA becomes useful and if only some part of the system requires up gradation there is no need to do the FMEA on the whole system all over again.

The documentation regarding FMEA needs the up gradation needs to be updated wherever there is a change made. Doing so will help to understand the effects on the system due to these changes. At suitable intervals should be taken for any update to be made in FMEA.

### **Generating the Failure Modes**

The failure mode is generally the way things fail, but this definition will cause confusion when working with a design at different levels of the development phase or in other words when the system does not execute in accordance to its specifications is termed as failed [8]. In OO-FMEA failure modes are defined as the negation or deviation of the design intents. Negation could be understood as the “product or system is not working at all”, and deviation would be the “the product or the system is not working as intended or expected” [2]. The potential failure modes are generated by formulating the negation and deviation of the design intents, while performing the OO-FMEA for software, this is considered as a golden rule and should be followed and strictly abide by it. Quality of the design intents matters to have a good accuracy of this step, the design intent should be made quite clear accurate and as brief as possible to have a good and well explained meaning, which will eventually lead to the accuracy of this step and improvement on the design.

When performing the FMEA it is taken under consideration that output of each object must be in accordance to the design intent, it must confirm the design intent, and if it is not the case then there is negation or deviation which is basically a failure mode.



**Figure 4-16 Types of Failure Modes**

### **The FMEA Template**

The clarification and explanation of the FMEA chart is important so as to have a better understating. The FMEA template is shown in 3.19 and its headings are explained one by one as follows,

#### **1. Object**

In the blocks under the column of “Object” the names of the objects is entered, the name of the object which contain the design intents. In our case we will put the name “Defroster” in it.

#### **2. Function**

When the fourth step of FMEA starts, it starts with the addition of the design intents sometimes called as intended functions, are put in to the 3rd column of the FMEA chart sheet named “Function” [8]. The syntax in which it should be written is of great importance i.e. verb of the design intent should come first showing its main function. For example the functions for the Defroster as stated earlier are added one by one in each column. The example of the function is shown in the figure 4.22.

#### **3. Potential Failure Modes**

It is defined as the number of possible ways in which a system, subsystem, product, or any process fails [26]. The design intents are discussed, explained and the possible failure modes are taken under consideration. Either negation or deviations are written in the next column named under “Potential Failure Mode”. The deviation can further be explained as any over function, unintended function or partial failure. It is of great importance that there should be discussed the failure mode for each design intent, sometimes a design intent may not have any failure mode in such case that design intent is not included in the FMEA process because without any potential failure, why bother including FMEA in this process.

#### **4. Potential Effects of Failure Modes**

Potential Effects of the Failure Modes are written in the next column named under “Potential Effects of Failure”. The Effects of the failures are the consequences of the failure modes to be faced by the end user. The effect of the failure is important to discuss here as on the basis of this, the Risk Priority Number (RPN) would be more accurate and the recommendations could be more effective and accurate. It is very important to be very precise in describing the failure effects.

## 5. Potential Causes Mechanisms

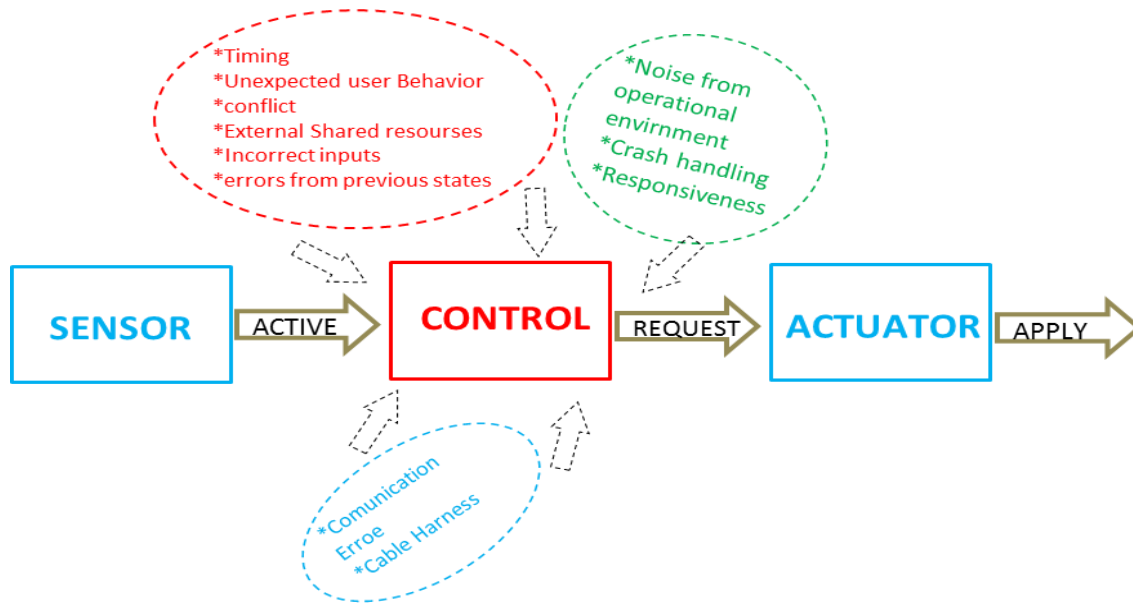
In complex system when OO-FMEA is done and when describing the effects of the failure modes, it becomes also very important that the causes Mechanism should also be discussed so that the root cause of the failure is eliminate or minimize. Cause mechanisms are basically the factors affecting the control process in reality. There can be more than one cause to any failure which is brain stormed and should be limited to design issues [26]. The complex system the emergence of different unwanted effects is a common phenomenon. Emergence is the way in which complex systems behave as a result if interactions, dependencies and other exchanges or influences that may or may not be intended.

[Input] SWITCH (activates) → CONTROL (Requests) → [output] ACTUATOR (Applies)

The cause of the failure mode is also discussed because it will also help in RPN. To have a detailed explanation figure 4.17 could be of more help to have a better understanding,

There are three categories of cause mechanism,

- \* The emergence occurrences of complex systems (Red Text)
- \* The noise factor (Green Text)
- \* The communication medium (Blue Text)



**Figure 4-17 Illustration the potential cause mechanism in complex structures**

The things which should be taken under consideration can be the timing that is how much time is taken to complete the action, is it good enough, or is it calibrated that it must not conflict with the other subsystem or subsystems etc.

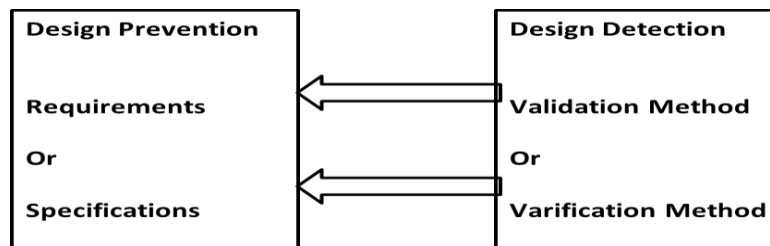
What are the other factors which are directly or indirectly affecting the system or effected by the system. What happens in case of errors or if there is noise from the operational environment. What about the cable harness or does it handles the physical objects properly, if there is any communication error. All these things are considered when designing the system and if there is anything not working properly or not working at all or not producing the desired output, then the failure modes are generated based on these.

#### 6. Current Design Control Prevention

There is a column named “Current design control prevention” contains the design preventions which are basically the documented requirements that eliminate the causes or constrain the potential failure modes [8]. These are preventions which are to be added and/or used to help eliminate the potential failures of the system. So when there are no possible preventions then this block is left and the must be proceed to the next column which is “Current design control detection”.

#### 7. Current Design Control Detection

The Design Prevention and Design Detection may cause confusion somehow, but these two are different with respect to their functions [8]. In case of Current Design Control Prevention, the requirements and specifications were mentioned to have a system prevented from the failures. But in case of current Design Control Detection, methods of validation and validation prevention are mentioned. The relationship between the two is described in figure 4.18.



**Figure 4-18 Design prevention and design detection**

#### **Severity, Occurrence and Detection**

All these three are rated between 1 to 10, based on the Severity, Occurrence and Detection of the design Intent, 10 being the highest and 1 being the lowest [2].

- **Severity**

In case of Severity it shows how severe the failure is so 10 means the very high severity ranking when a potential failure mode affects the safe vehicle operations and 1 being the lowest and to be less worried about [2]. As the system may or may not compose of different sub-systems and sub-system is compose of different components. So if a component which may affect other components in the same sub-system or in other sub-systems may lead to the loss of function and will be indicated in high “*severity*”. Severity number is low for any sub-system which is unique, does not have any interdependencies and which also may not lead to the loss of function. How sever a failure mode can be is based on the internal criteria [26]. The severity figure is shown below

Effect	Criteria: Severity of Effect on Product (Customer Effect)	Rank
Failure to Meet Safety and/or Regulatory Requirements	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	9
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).	8
	Degradation of primary function (vehicle operable, but at reduced level of performance).	7
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable).	6
	Degradation of secondary function (vehicle operable, but comfort / convenience functions at reduced level of performance).	5
Annoyance	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (>75%).	4
	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by many customers (50%).	3
	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%).	2
No effect	No discernible effect	1

**Figure 4-19 Criteria for the selection of level of severity [9]**

- **Occurrence**

In case of Occurrence, how often this failure may occur or occurs and is based on the previous failures [2]. The ratings mentioned in the figure 4.20 are based on the internally defined criteria and rating should be used while performing the FMEA [26]. This is measured in response to the system in used and the number is taken under consideration by the owner. Also in this case 10 is consider having a high persistent failure and it can be defined as 100 products out of 1000 products if the problem occurs and 1 being the lowest such as 1 product out of 1000 products. These numbers can be varied according to the standards.

Likelihood of Failure	Criteria: Occurance of cause Design life/reliability of item/vehicle	Criteria: Occurrence of Cause – DFMEA (Incidents per item/vehicle)	Rank
Very High	New technology/new design with no history.	$\geq 100$ per thousand $\geq 1$ in 10	10
High	Failure is inevitable with new design, new application, or change in duty cycle/operating conditions.	50 per thousand 1 in 20	9
	Failure is likely with new design, new application, or change in duty cycle/operating conditions.	20 per thousand 1 in 50	8
	Failure is uncertain with new design, new application, or change in duty cycle/operating conditions.	10 per thousand 1 in 100	7
Moderate	Frequent failures associated with similar designs or in design simulation and testing.	2 per thousand 1 in 500	6
	Occasional failures associated with similar designs or in design simulation and testing.	.5 per thousand 1 in 2,000	5
	Isolated failures associated with similar designs or in design simulation and testing.	.1 per thousand 1 in 10,000	4
Low	Only isolated failures associated with almost identical design or in design simulation and testing.	.01 per thousand 1 in 100,000	3
	No observed failures associated with almost identical design or in design simulation and testing.	$\leq .001$ per thousand 1 in 1,000,000	2
Very Low	Failure is eliminated through preventive control.	Failure is eliminated through preventive control.	1

**Figure 4-20 Criteria for the selection of level of likelihood of Occurrence [9]**

- **Detection**

It is the detection of the failure in the product and is based on the internally defined criteria. if the number is 10 for detection of the failure mode is very hard and it is said that the Design Control will not/or cannot detect the potential cause/Mechanism and failure mode, and when this number is 1 it is said that the Design Control will almost certainly detect a potential

cause/Mechanism and Failure mode (very easy to detect). The detection table is shown below,

Opportunity for Detection	Criteria: Likelihood of Detection by Design Control	Rank	Likelihood of Detection
No detection opportunity	No current design control; Cannot detect or is not analyzed	10	Almost Impossible
Not likely to detect at any stage	Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g., CAE, FEA, etc.) is not correlated to expected actual operation conditions.	9	Very Remote
Post Design Freeze and prior to launch	Product verification/validation after design freeze and prior to launch with pass/fail testing (Subsystem or system testing with acceptance criteria such as ride and handling, shipping evaluation, etc.).	8	Remote
	Product verification/validation after design freeze and prior to launch with test to failure testing (Subsystem or system testing until failure occurs, testing of system interactions, etc.).	7	Very Low
	Product verification/validation after design freeze and prior to launch with degradation testing (Subsystem or system testing after durability test, e.g., function check).	6	Low
Prior to Design Freeze	Product validation (reliability testing, development validation tests) prior to design freeze using pass/fail testing (e.g., acceptance criteria for performance, function checks, etc.).	5	Moderate
	Product validation (reliability testing, development validation tests) prior to design freeze using test to failure (e.g., until leaks, yields, cracks, etc.).	4	Moderately High
	Product validation (reliability testing, development validation tests) prior to design freeze using degradation testing (e.g., data trends, before/after values, etc.).	3	High
Virtual Analysis – Correlated	Design analysis/detection controls have a strong detection capability. Virtual analysis (e.g., CAE, FEA, etc.) is highly correlated with actual or expected operating conditions prior to design freeze.	2	Very High
Detection not applicable; Failure Prevention	Failure cause or failure mode can not occur because it is fully prevented through design solutions (e.g., proven design standards, best practice or common material, etc.).	1	Almost Certain

**Figure 4-21 Selection level due to chances of detection of Failure Mode [9]**

#### 8. Risk Priority Number (RPN)

Risk Priority Number (RPN) is a decision factor based on the product of three ratings which are severity, Occurrence and Detection based on the standardized criteria [2]. These ratings are scaled with numbers from 1 to 10. According to the criteria there are different levels of acceptance of the Risk Priority Number. The acceptance level of RPN depends on the ambition of design team; level of perfection of the product required and is determined by the lowest value of detection [26]. But in general cases when the RPN is greater than 100, then it requires the necessary and recommended actions. When the design intent with greater RPN is taken under consideration and the necessary actions are taken, the lower RPN after the actions taken is basically the outcome. As it is been said earlier that the RPN is the product of Severity, Occurrence and Detection, assigning the level for all these three requires attention and is a challenge. To have a more accurate result regarding these knowledge on quality history, Software and Hardware reliability data, component specifications and system design contribute more. There are some tables given to the FMEA team to get the help from in order to label the level.

## 9. Recommended

In this block the recommendations and suggestions regarding the design intents are taken to have a backup strategy against failure modes. The level of attention required to consider any design intent for some recommended actions is based on the respective RPN [26].

No	Object	Function	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Causes/ Mechanisms of Failure	OCC	Current Design Control Prevention	Current Design Control Detection	DET	RPN	Recommended
1	Defroster	1	No increase in headlevel temperature	effects the climate comfort. It would be cold inside the cabin. Max defrost of windscreen effects automatic air flow, air	5	Control algorithm malfunctioned	1	Higher calibratable headlevel setpoint is used a few degree above the highest normal set point	Testing to varify the prevention	2	10	Verify the degree of effect
2	Defroster	2	Unable to maintain the energy balance and can not calibrate the air flow	Fluctuating temperature and airflow customer dissatisfaction	6	Incorrect mapping of algorithm	3	Map of steady state airflow and look-up table for breakpoint for max heat and	Computer simulation and testing	3	54	
3	Defroster	3	Un necessary requirement as defroster is not a permanent function so no need for this function									
4	Defroster	4	No change in the wanted head level tempertaure when defroster air flow is deviated	effects the climate comfort. Max defrost of windscreen effects automatic air flow, air distribution and temperature control. It will not enhance	3	In correct parameters and/or parameters calculation and/or Control algorithm malfunctioned	4	calculation of delta dew point and dew point also the Higher calibratable headlevel setpoint should be used a few degree above the highest normal	Testing to varify the prevention	6	72	Verify the calculation, the direction of air and verify the effect of degree

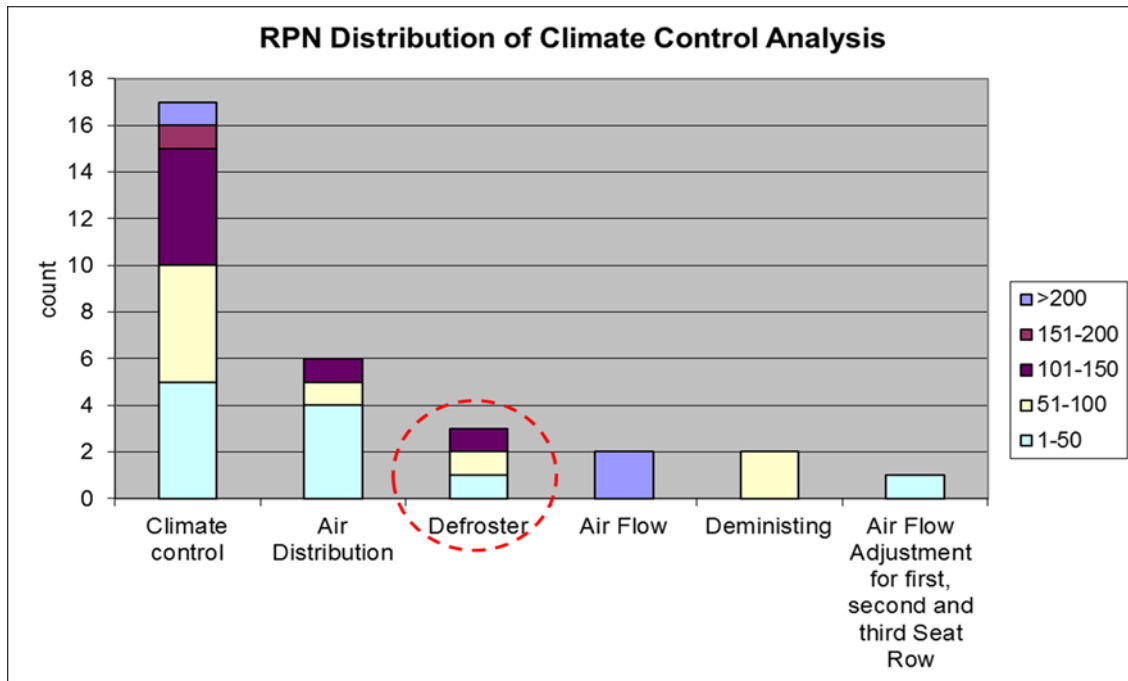
**Figure 4-22 Generation of Failure Modes and RPN**

When the Failure Modes are generated and RPN is calculated, a histogram is made based on the distribution of RPN shown in the figure 4.24. The histogram shows the number of design intents which has the RPN and the number of logical objects taken under consideration when doing the FMEA. The design intents are indicated with different colors which show the severity of the situation. The histogram basically gives the information about how many logical objects and design intents are needed to be taken care of. When the necessary measures are taken based against the design intents of the logical objects the FMEA is done again which is basically the step number 5 of OO-FMEA approach.

Count of Object	RPNCL					
Object	1-50	51-100	101-150	151-200	>200	Grand Total
Climate control	5	5	5	1	1	17
Air Distribution	4	1	1			6
Defroster	1	1	1			3
Air Flow					2	2
Deministing		2				2
Air Flow Adjustment for first, second and third Seat Row	1					1
<b>Grand Total</b>	<b>11</b>	<b>9</b>	<b>7</b>	<b>1</b>	<b>3</b>	<b>31</b>

**Figure 4-23 Pivot Table**





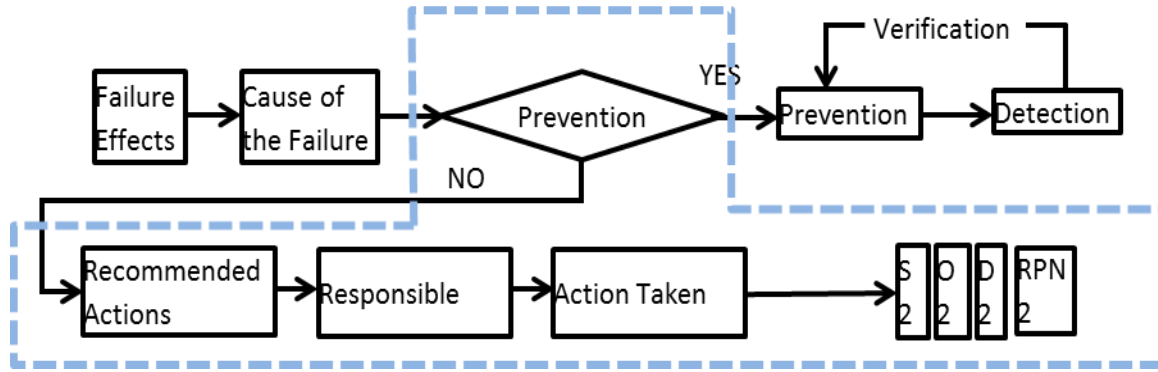
**Figure 4-24 RPN distribution**

After performing the FMEA process on the design intents in defroster are categorized based on the level of severity shown by the RPN.

#### 4.5.5 OO-FMEA 5<sup>th</sup> Step (Complete the FMEA)

Step 5 includes the completion of the FMEA process according to methodology. It would not be entirely wrong if step 5 is said to be the validation of the FMEA process and failure modes. When the FMEA process is done in step 4 there were some failure modes being generated and causes of the failure modes were identified and all the Severity, Occurrence and Detection are taken care of. Then there is a column labeled as Prevention, if there is some prevention for any failure mode and is mentioned then the process goes all the way to the requirement of the specifications and ultimately to the detection. If there is some problem which still persists then it is verified again.

As shown in figure 4.25, there are some cases where prevention might be a bit of a problem and is not there, so in such cases it goes to the recommended actions regarding the Failure mode and things, objects or the subsystems which are responsible to such failure modes are highlighted. Of course it needs some actions to be taken against these failure modes. When these actions are taken then Severity, Occurrence and Detection and RPN are generated again to see if these are reduced and this reduction in the RPN is shown as a result.



**Figure 4-25 Completion of FMEA**

After the completion of step number 4, the step number 5 is used testing the product and validation and verification of the results as shown in the figure 4.25 and as the heading shows it is the completion of FMEA.

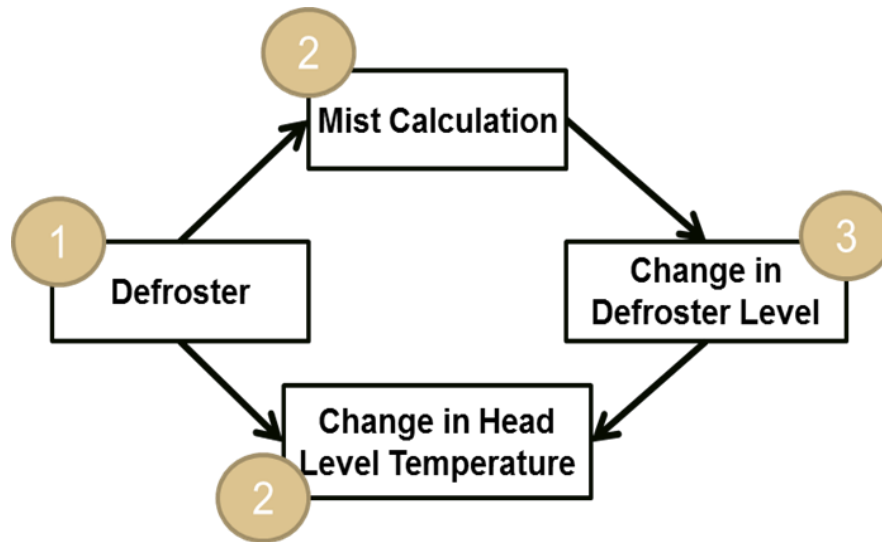
#### 4.6 1<sup>st</sup> Recommendation

After the implementation of OO-FMEA on the Climate System and specifically on the Defroster function and looking deep in to the design intents of the “Defroster”, there are some recommendations which in the process of “OO-FMEA” are considered as results. In case of Defroster by looking in to design intents, is shown that the defroster is turned ON manually when the need of the defroster is felt by the user. When there is mist on the screen then the defroster is turned ON and the calculations regarding the Head Level Temperature are done and the head level temperature is set to maintain the climate comfort after the defroster is turned ON.

When the defroster is turned ON, it has some affects the Climate System. Though the requirement of setting the head level temperature again is better to maintain the climate comfort, but when there is change in the defroster level (as the defroster runs on different levels based on the requirement and mist conditions) the calculations regarding the changing the head level temperature again according to the new setting is done. And all this process is shown in the figure 4.26 based on all the four design intents. The four design intents are shown below,

1. Choses a separate calibratable ambient temperature dependent head level set point (typically few degree above the highest normal set point) for the first seat row when max defroster is selected (turned ON).
2. Calculates dew point and the difference between windscreen temperature delta dew point, convert relative humidity and air temperature of compartment from humidity sensor into dew point.
3. Perform demisting by increasing the defroster airflow according to the demand of demisting based on the calculated mist risk (Humidity sensor) and (ambient temperature).

4. Change the wanted head temperature for the first seat row when defroster airflow is deviated from the base defroster airflow. Change should be calibratable and depend on ambient temperature and magnitude of the defroster air flow. The flow of the commands is shown in the figure 4.26, with the order of the execution. The arrows show the direction of flow of the commands according to the design intents and the numbers show the order.



**Figure 4-26 Flow of the commands according to the design intents**

#### 4.6.1 Explanation

According to the “Defroster” design intents the figure 4.26 showing that when the defroster is turned ON there are two functions which are activated, i.e. Mist Calculation and Change in the Head Level Temperature.

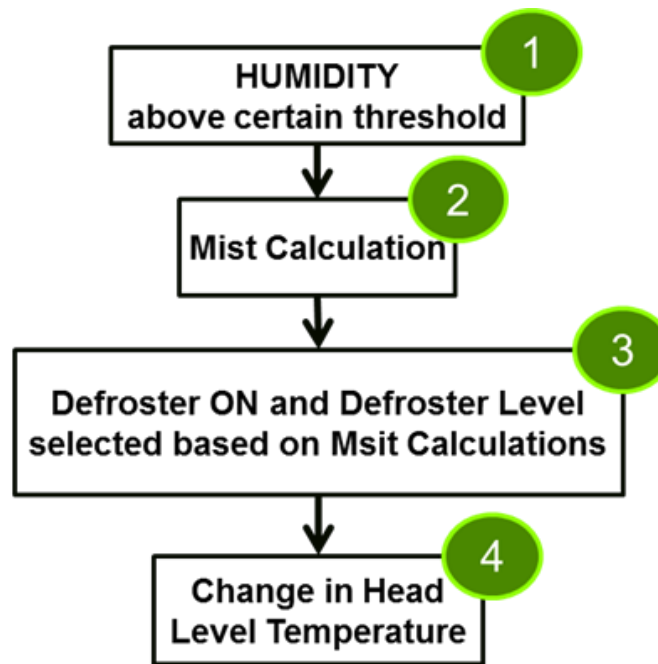
And the head level temperature is changed when the defroster is turned ON as the defroster effects the climate in the passenger compartment. When the defroster is turned ON the relatively cool air is directed towards the windscreen. Due to that there is a change in temperature which is felt by the user. To overcome that change the head level is also changed.

The mist on the screen is calculated so that the level for the defroster is decided. When there is a change in the defroster, the head level temperature is also changes according to the change in the level of the defroster and when the defroster is turned OFF the head level temperature is returned back to, where it was before the defroster was turned ON.

#### 4.6.2 Suggestion regarding 1<sup>st</sup> Recommendation

There is a suggestion regarding this requirement is to make the defroster system automatic, which means that the user should not be bothered to feel the need for defroster. The main reason which cause the mist to occur is the level of humidity in the compartment so when the level of humidity rises up to certain threshold and the mist on the screen is already been calculated then it should be automatically judged by the Climate System whether there is need of the defroster or not. The level of defroster is calculated based on the level of the mist

on the wind screen so when the defroster is turned ON after the calculation of the mist on the windscreen, then it should start from the same level which is required to cope with the level of the mist on the wind screen. Once the level of the defroster is decided based on the level of the mist on the wind screen, the head level should be set accordingly to maintain the climate comfort. The direction of the defroster flap also plays an important role in the effectiveness of the defroster, so the direction of the flaps must be considered important. The recommended flow of the commands is shown in the figure 4.27,



**Figure 4-27 Recommended flow of commands for automatic Defroster**

#### **4.7 2<sup>nd</sup> Recommendation maintaining the humidity level**

As seen earlier when the defroster is turned ON there is always a set of commands and function following the defroster function, sometimes the temperature in the passenger compartment is calibrated according to the changes in the defroster function. Also when the defroster is turned ON, there is abrupt change in the climate of the passenger compartment which can cause the customer dissatisfaction issues. As defroster function is turned ON manually when there is mist on the screen and it is hard to see through. The main reason behind misting is the level of humidity, when the level of humidity is above the normal and other conditions are fulfilled misting occurs. And after doing the analysis on the Climate System it can clearly be seen that there are different logical objects which consists of many design Intents collectively, that holds many complex calculation which are doing in parallel to do just one job that is "DEMISTING" on the wind screen and side windows. Spending time, energy and engineering work to remove demisting, it should be possible just to calculate the humidity level and control it efficient enough so that instead of defroster function just maintain the humidity level, in a strict fashion no matter how fast the changes are, the actions should be made fast accordingly. Humidity must be maintained to the level of comfort (no dry

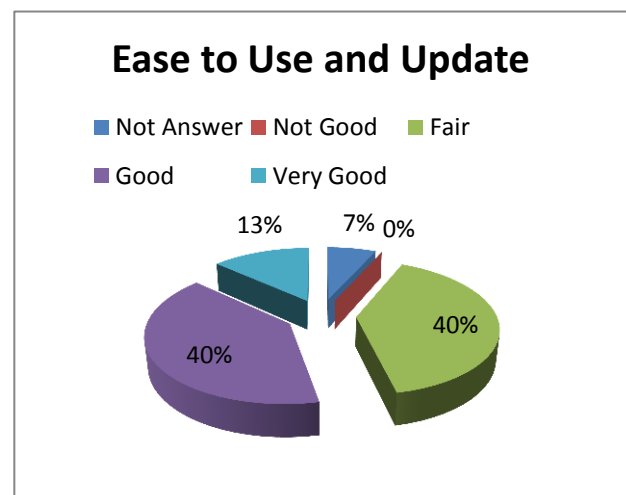
eyes etc.) depending upon different ambient and internal conditions. The level of the comfort can be change/selected based on the user requirements and/or regions in which the vehicle is to be used.

#### 4.8 Survey: Comparison between traditional FMEA & OO-FMEA

A survey was conducted within the organization about the advantage of OO-FMEA over traditional FMEA. That survey was composed of different questions which were asked to the people who have both performed the traditional FMEA and OO-FMEA and the results are shown in the form of pie charts. The results were more than good in favour of OO-FMEA. The purpose of this survey is to get some feedback from the users.

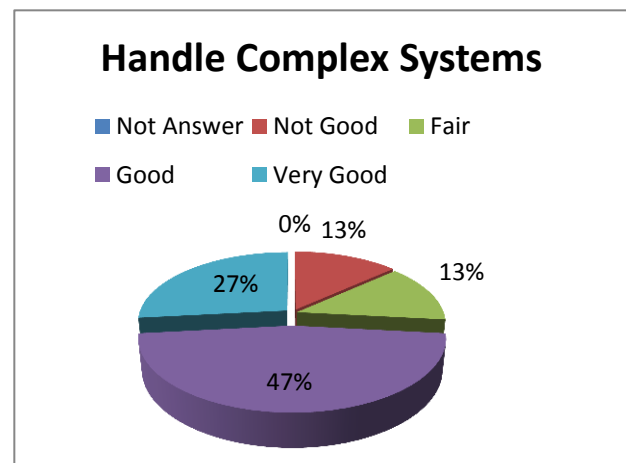
##### 1. Ease to use and Update

OO-FMEA is very easy to use and update, when asked in the survey, the answers in favour of OO-FMEA were ranging from fair to very good occupied 93% of the graph and rest of the 7% did not answer.



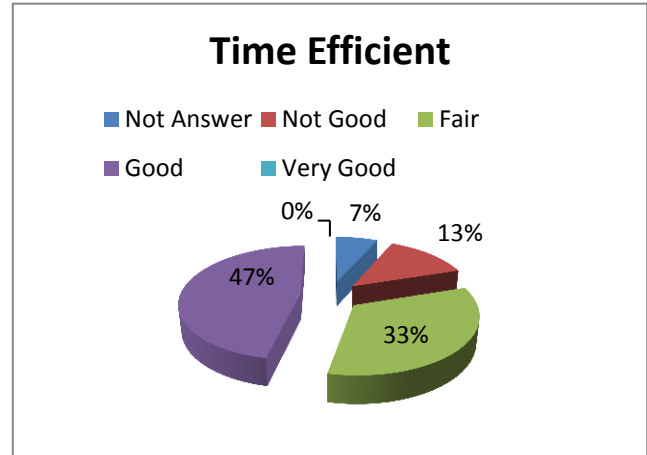
##### 2. Handle Complex Systems

OO-FMEA can handle complex systems, when asked in the survey, the answers in favour of OO-FMEA were ranging from fair to very good occupied 87% of the graph and rest of the 13% said it is not good.



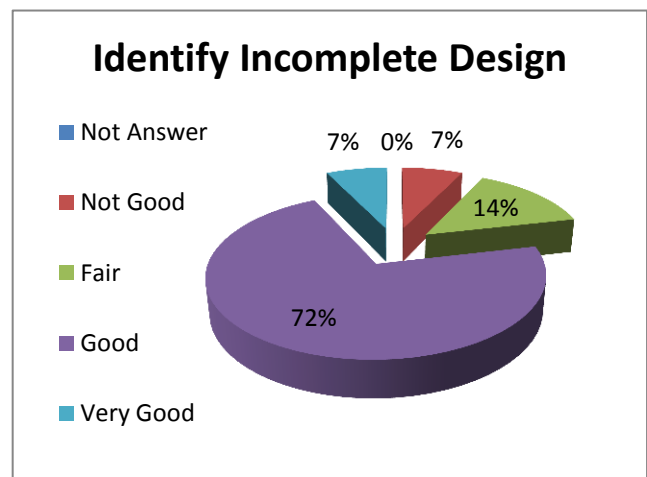
### 3. Time Efficient

OO-FMEA is time efficient, when asked in the survey, the answers in favour of OO-FMEA were ranging from fair to good occupied 80% of the graph and rest of the 13% said it is not good and rest 7% did not answer.



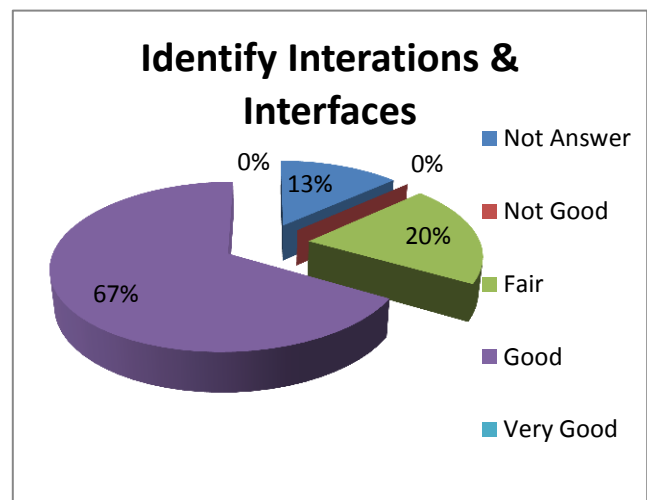
### 4. Identify Incomplete Design

OO-FMEA is useful to identify incomplete designs, when asked in the survey, the answers in favour of OO-FMEA were ranging from fair to good occupied 93% of the graph and rest of the 7% said it is not good.



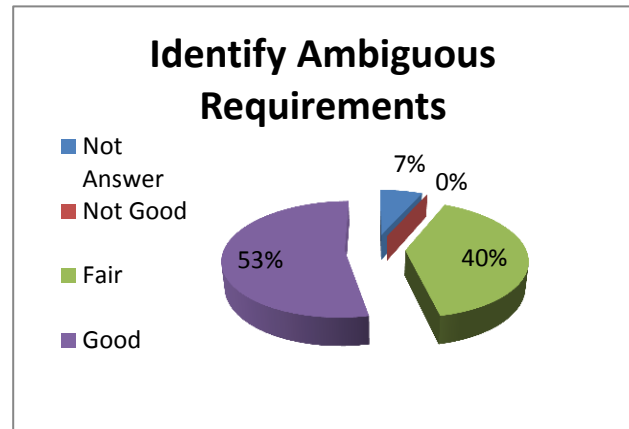
### 5. Identify Interactions & Interfaces

OO-FMEA is useful to identify Interactions and Interfaces, when asked in the survey, the answers in favour of OO-FMEA were ranging from fair to good occupied 100% of the graph.



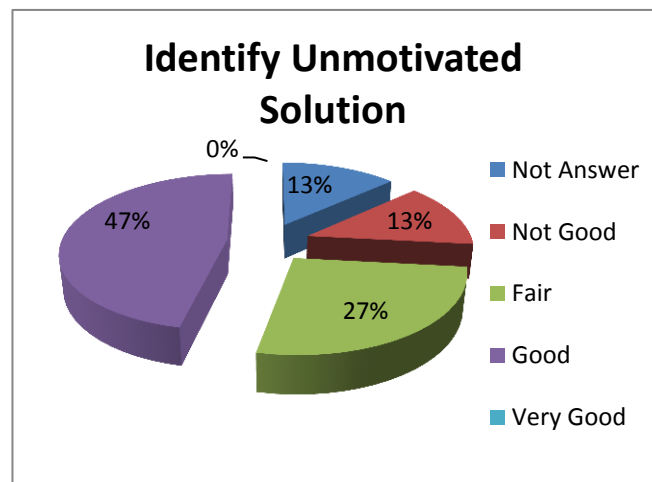
## 6. Identify Ambiguous Requirements

OO-FMEA is useful to identify Ambiguous Requirements, when asked in the survey, the answers in favour of OO-FMEA were ranging from good to fair occupied 93% of the graph and rest of the 7% did not answer.



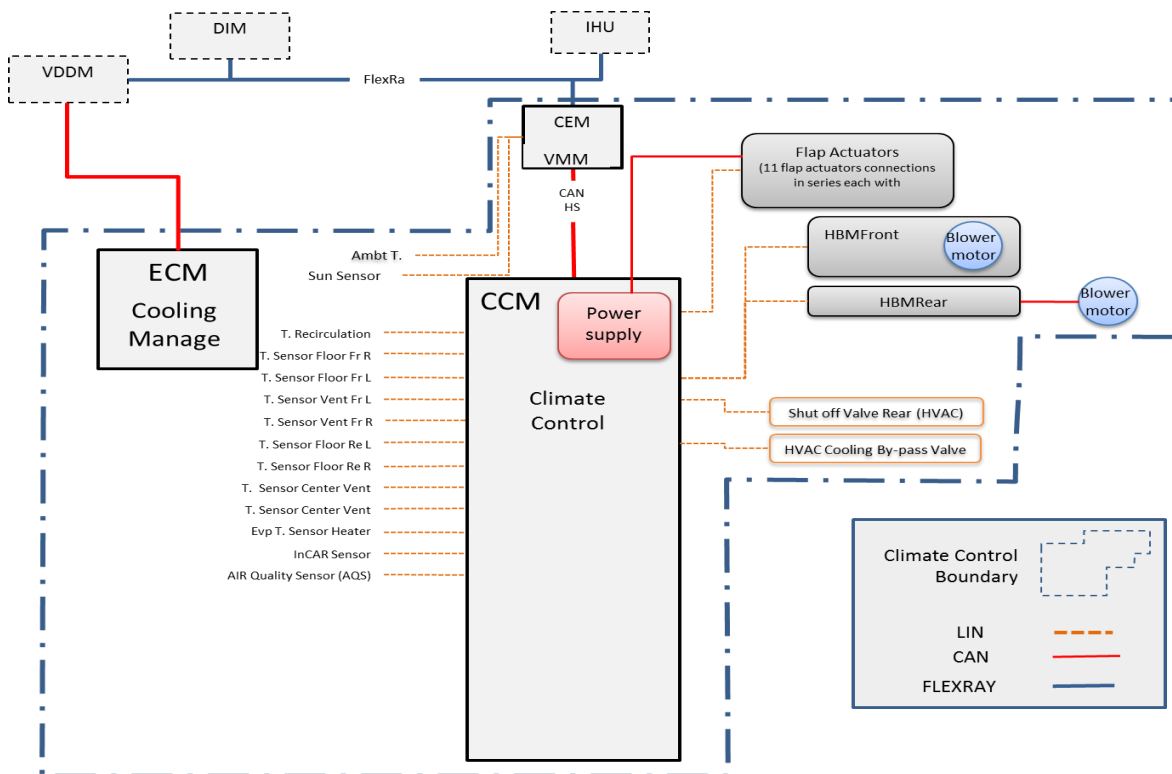
## 7. Identify Unmotivated Solution

OO-FMEA is useful to identify Unmotivated Solutions, when asked in the survey, the answers in favour of OO-FMEA were ranging from very good to fair occupied 74% of the graph, 13% said it is not good and rest of the 13% did not answer.



## 5 Results

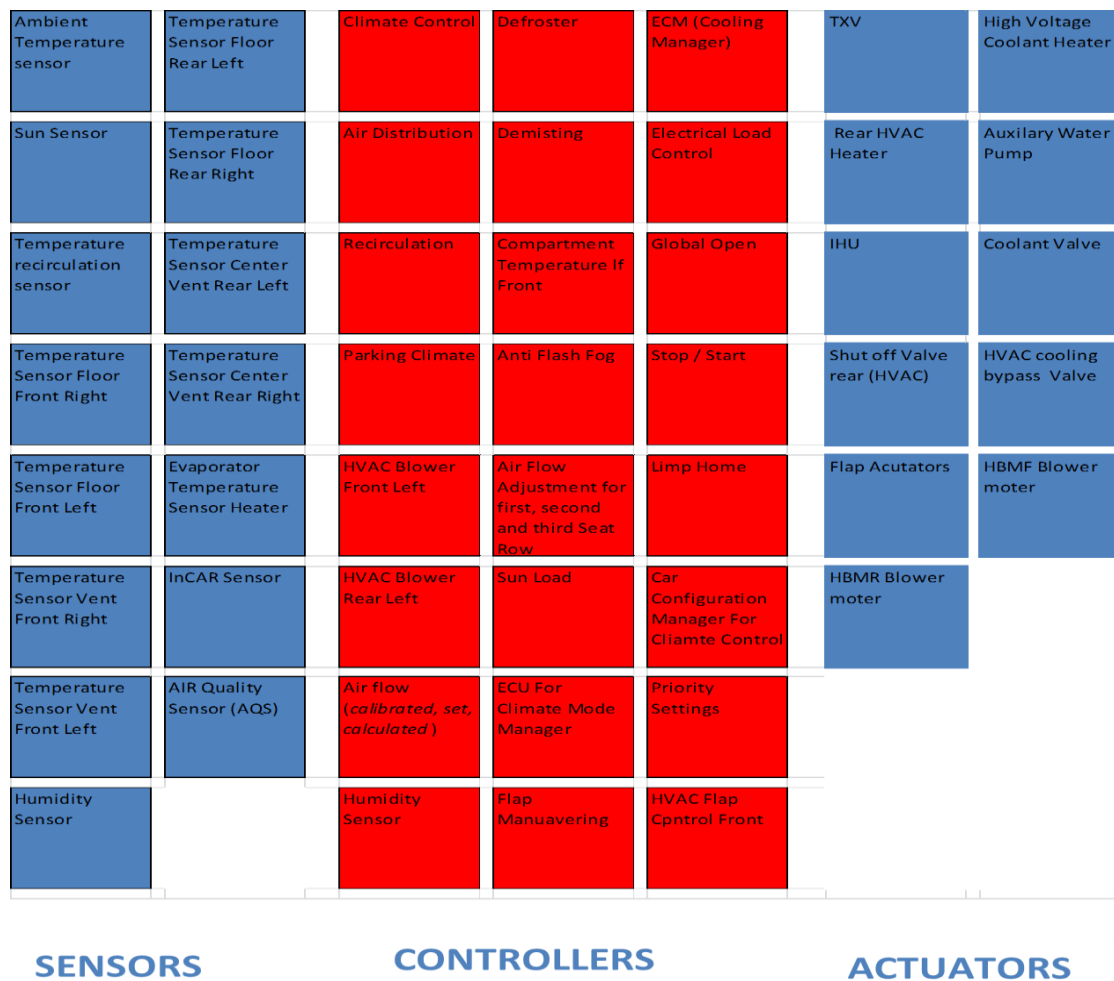
It is an advantage of OO-FMEA approach over traditional FMEA that it starts with the conceptual structure models (SW) or modules (HW), input and output components, external shared resources, and an appropriate boundary. Due to which is unnecessary complications are avoided. Thermal Management Climate is a big and complex system. By implementing OO-FMEA interactions and interfaces between the components, external shared resources, system overlaps and behavior of the components became clearer which helped to have a better understanding of the system. The climate system along with its boundary line are shown below,



**Figure 5-1 Boundary of Climate System**

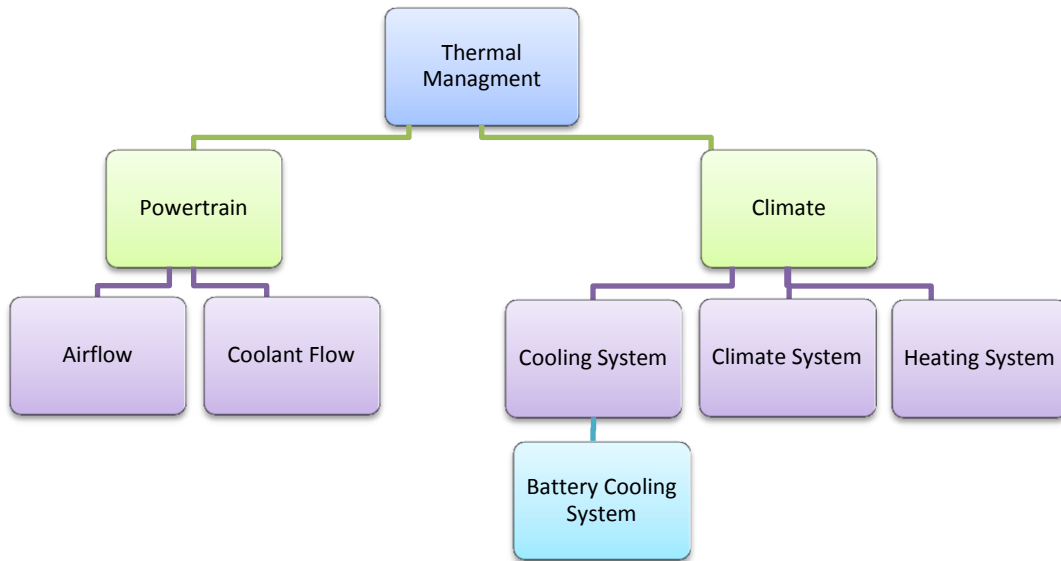
Another advantage of OO-FMEA approach is that all the components and their behaviors are visible after its implementation. In the Climate System the sensors (inputs), controller and actuators (output) is visible which helps the better understanding of the system. All these are taken under consideration when designing the system and if there is anything not working properly or not working at all or not producing the desired output, then the failure modes are generated. In figure 5.2 all sensors, controllers and actuators which are present in the Climate System are displayed. The controllers are in the red boxes as these are logical objects, whereas sensors and actuators are in the blue boxes which shows these are physical objects.





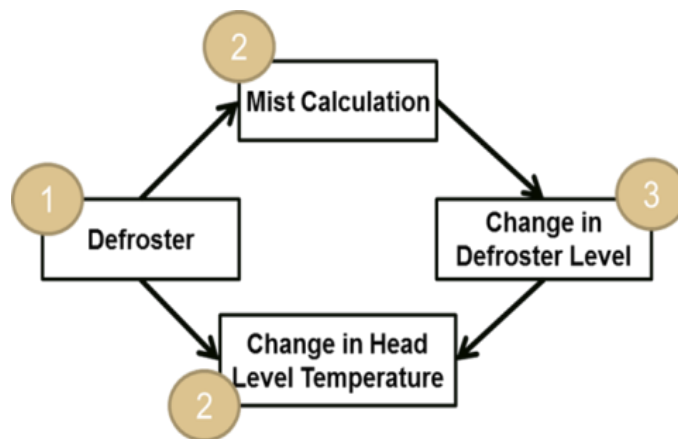
**Figure 5-2 List of Sensors, Controllers and Actuators**

OO-FMEA starts with the construction of system architecture which includes the system boundary and the list of inputs, Controllers and outputs. The documents based on these findings has enough information that if at any point the system is easy to learn (**usability**) and if there is any up gradation or change (**Update**) required, it can be made without wasting time by starting to study the system all over again. After reviewing system structure and behavior of the components it became clear that the division of thermal management climate at VCC needs some improvements. Thermal management Climate is now divided into three sub-systems now i.e. Cooling System, Heating System and Climate System. Whereas the battery Cooling system under the Cooling System. This is shown in the following hierarchy diagram



**Figure 5-3 Modified structure after implementation of OO-FMEA**

Another advantage of OO-FMEA is that it helps to find out the ambiguous requirements. In 1<sup>st</sup> recommendation the ambiguity of the defroster is discussed. When defroster is turned ON mist on screen is calculated and head level temperature is changed. Based on the mist calculations the defroster level is selected and again the head level temperature is changed based on the change in the defroster level. As shown in the figure 5.4,



**Figure 5-4 Flow of commands according to design intents**

Another advantage of OO-FMEA is that user will get the complete behaviors of system in an easy way through logical physical and attributes objects which helps in understanding a system easily as it includes all the elements which are inside the system boundary (Climate System). All the objects of the climate system are shown in the figure 5.5.

HVAC blower Module F	HVAC blower Module R	Climate Control	Defroster	ECM (Cooling Manager)	Power Logics	Temperature Sensors
IHU	CPM	Air Distribution	Demisting	Electrical Load Control	Sun Sensor	Noise Perception
TXV rear VAC	RHVAC Heater	Recirculation	Compartment Temperature If Front	Global Open	Assembly and Service	Forced Cooling
LIN	Auxiliary Water Pump	Parking Climate	Anti Flash Fog	Stop / Start	Diagonostics	Responsiveness
FlesRay	HV Coolant Heater	HVAC Blower Front Left	Air Flow Adjustment for first, second and third Seat Row	Limp Home	Legal Requirements	Crash Handling
Coolant Valve	INCAR sensor	HVAC Blower Rear Left	Sun Load	Car Configuration Manager For Climate Control	EMC	
Flap Acutators	central Electronic Module	Air flow (calibrated, set, calculated)	ECU For Climate Mode Manager	Priority Settings		
Air Quality sensor	TEM	Humidity Sensor	Flap Manuavering	HVAC Flap Cptrol Front		

**Figure 5-5 Physical, Attributes and Logical objects after implementation of OO-FMEA**

# 6 Conclusion and Future work

## Conclusion

Current trend in the automobile industry is to introduce highly intelligent yet comfortable and safe vehicles to achieve the higher level of customer satisfaction. To achieve such reliability, the products must be reliable and the chances of problems or failures to occur in them must be very low. The FMEA is a tool to eliminate or reduce any failure modes of system. Lesser the failures are more reliable the product there is. Though being a widely used approach it also requires some other design activities which are done before, along with and after FMEA to take full advantage of the FMEA process. Quality of FMEA results are dependent on the quality of inputs to FMEA which are provided by OO-FMEA. When it comes to the complex systems like Climate System, traditional FMEA alone is not good to handle these. In complex systems traditional FMEA treats each failure mode as independent which does not show its dependencies or effects on the other components, this is solved by the use of OO-FMEA where interactions and interface defines the dependencies and effects of components over the others. In this thesis OO-FMEA is introduced and implemented on the Climate System. This approach is quite capable of handling the complex systems. Unlike traditional FMEA, this approach is very good when it comes to do any advancements or applying the up gradations on any system. In OO-FMEA to find out the dependencies and interactions between the objects, structure and boundaries of the system are of great help. These boundaries also help to find out the dependencies of some objects over the other. It helps engineers to decide; which of the objects need the Failure generation. It has a better control over the starting of ending point because it starts with the making of system structure and making of the system boundary.

## Future Work

Climate system is basically a control oriented system which is composed of sensors, controllers and actuators. Data from sensors is input to the system where certain actions are performed based on the requirements and output data is given to the actuators to perform the actions accordingly. Control system is basically a combination of certain processes and interconnected components designed to achieve desired goals which take some inputs and provide controlled output. OO-FMEA must also be applied to other types of systems such as Transaction Processing Systems (TPS) and Data Processing Systems (DPS).

OO-FMEA should be implemented on TPS because this being a real time system has to be faultless. To handle requests from multiple clients to updates to shared data resources is a transaction Processing System [27]. TPS is a type of information system in which collection, retrieval, modification and storage of data transactions is done. TPS is a real time system in which an immediate response is given while the processing is completed. Transaction is

basically a series of decisions/operation taken on shared data all together and must be real time and it must complete or fail its task as a unit. It must be independent of all other processes which are running at the same time. In TPS if the process is completed it must update both, from where the data is taken and to which data is transmitted. In TPS the data is shared between numerous users, the requests are processed in real time. It may entertain multiple requests at the same time and is called batch processing. In TPS there is a term called time sharing which is basically the distribution of time between multiple users so as to entertain their requests at the same time. Though this system gives the impression that the user solely control over the system but it is shared. The Transaction processing cycle includes data entry, generation of reports, analysis handling. The example of TPS is Automated Teller Machine (ATM).

OO-FMEA should be implemented on Data Processing Systems (DPS). It is a type of information system which includes accepting a set of data input, processing and storage of data and in response providing a set of outputs [28]. It runs a check for any possible errors or if data is not in accordance with required specifications, this process is called validation. It provides information (alerts) about the errors and if data is correct then it records/save it. Data processing system is a complex system which may include the encryption of data, accumulation of multiple pieces of data, arrangement of data with specific measures according to set standards, and analysis of data. In data processing activities, data has to be stored for future use as it may not be needed instantly. Unlike control systems where the efforts are made to increase the efficiency of control, in data processing system processing, storing, collection and retrieval of data is done so that the difficult and frequently repeating tedious operations are processed, For example the library management system.

After reviewing thermal management climate system, based on the behaviours and interactions it was best suited to make three sub-systems out of it i.e. Climate System, Cooling system and Heating system. In Climate System the heating of the components were considered with the help Heating Manager. The heating system includes the heating of passenger compartment and is important when discussing the passenger compartment comfort. It was done in order to make the system less complex and the heating components such as seat heating and steering heating were considered under the heating manager and FMEA is yet to be completed on this system. OO-FMEA has been implemented on Cooling System and Climate System but Heating System is not yet completed and it is recommend that OO-FMEA should be completed for heating system.

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