Design of the Environmental Control System of an Unmanned Aerial Vehicle through the MBSE

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***Abstract*—Current transformation of the aircraft industry promotes a transition from the document-based to the model-based approach. In this paper, the design of the Environmental Control System (ECS) of an Unmanned Aerial Vehicle (UAV) is developed. This case is exploited to drive the Model Based Systems Engineering (MBSE) implementation towards an effective reuse; to interoperate the functional modelling based on the IBM tools with the numerical simulation provided by the AMESIM® toolbox; and to define a suitable process of heterogeneous simulation, while performing the trade-off activity, through a traced allocation of requirements.**

Keywords—MBSE, System Engineering, Heterogeneous Simulation, Environmental Control System (ECS), Unmanned Air Vehicle (UAV), Mechatronics.

I. INTRODUCTION

In the Unmanned Aerial Vehicle (UAV), the pilot is surrogated by a main artificial intelligent system, which exploits some subsystems to split the control action in several functions [1]. This strategy allows reducing size and weight of the aircraft, as well as its cost. The flight control is managed by an on-board computer, and remotely by a pilot, operating at the Ground Station (GS). All the flight parameters are communicated by the UAV to the GS, but the UAV system is even capable of actively react to any occurring failure, while warning the ground operators. The UAVs are classified in relation to their dimensions, maximum altitude and autonomy. In this case a "Medium Altitude Long Endurance (MALE)" is analysed. It flies at 500 m through 15000 m, for up to 24 hours. It performs the aerial surveillance, within a range of 500 km. The mission is even a matter of classification. The "Environmentally Critical Role" exploits the UAV to explore poorly populated areas. Therefore, it is usually smaller and lighter than other UAVs, and fuel consumption, emissions and noise must be kept as small as possible [2]. This role is extremely demanding in terms of performance. Particularly, it affects the design of the UAV subsystems, as the "Environmental Control System" (ECS). It performs the thermal control of the avionic bay, where avionic systems are installed. The ECS reacts to the kinetic heating effect, induced on the aerodynamic surface by air friction, to the solar radiation, to the heat produced by the avionic equipment in operation. Those heating phenomena are very crucial, since all the UAV functions are controlled by the electronic equipment stored inside the avionic bay [1]. High temperature can affect the reliability of avionics, and may lead to some fails in piloting, propelling, manoeuvring or in the flight dynamics. The prevention of risk associated to fails in flight stability and control depends mostly on the effective thermal control of avionic bays. Therefore, an effective cooling system is needed, despite of temperature decreasing in atmosphere, with altitude. Two technologies are currently used, namely the Air Cycle (ACS) and the Vapour Cycle Cooling Systems (VCS). Selecting between those two is never trivial, since many parameters affect the ECS performance. The trade-off analysis sets up a preliminary allocation of requirements to functions, and then checks the system performance of some structural solutions, to which functions are allocated [3]. To perform the last activity a heterogeneous simulation environment, where functional and physical models are integrated, is needed and its compliance to the technical standards must be demonstrated. This action is here accomplished by means of the Model Based Systems Engineering (MBSE) [3], which exploits the methodology, tools and languages of the Systems Engineering to provide the system integration. Once that the tool chain is set up, a bright organization of digital modelling must be promoted to reduce the complexity of process management, as is herein described, to achieve an effective reusability of models.

II. SYSTEM DESCRIPTION

The ECS is currently developed by resorting to two main technologies, which exploit either air or vapour as a mean for the heat exchange.

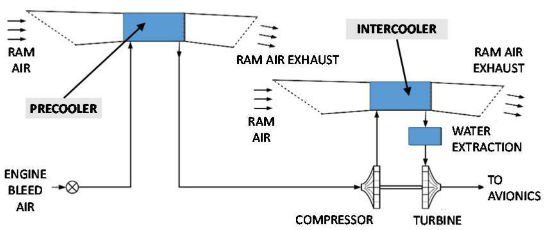

Fig. 1. Air Cycle Cooling System

A. *Air Cycle Cooling System*

The Air Cycle Cooling System layout is depicted in Fig.1 [4]. The air bleed of engines is cooled by a dedicated unit. Air flows from a stage of the high pressure-compressor, through a valve, which decreases its pressure. It goes then to a pre-cooler, where the heat exchange is performed. The pressure and temperature of air are increased by the compressor, connected to the turbine. A second heat exchange occurs inside the inter-cooler, where temperature decreases. The water content is removed. Finally, the turbine regulates the output temperature and pressure of air. The above described system is simple, reliable, and lighter than the system based on the vapour cycle, but the air flow required to engines is relevant. Therefore, the performance of engines is lower, and the drag induced by some large pipes installed is larger.

B. *Vapour Cycle Cooling System*

This cycle is closed, heat is exchanged through the evaporation of a cooling liquid. It passes through a compressor, where temperature and pressure increase, and then is cooled by a condenser. Before passing through the evaporator, it is expanded by a valve (Fig.2).

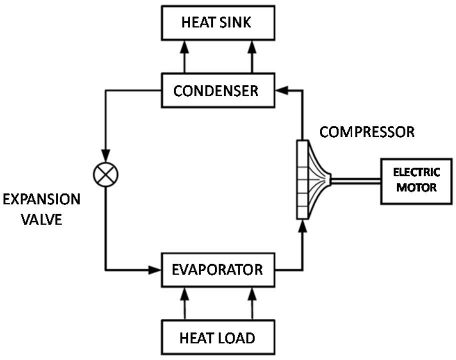

Fig. 2. Vapour Cycle Cooling System.

This solution performs better than the air cycle, but within a defined range of temperature, because of the maximum temperature achievable by the cooling liquid. The overall weight of this system is larger.

III. GOALS AND METHOD

Considering the two solutions above described, the trade-off activity can be suitably performed only by allocating the requirements to the ECS functions and components, and then evaluating its performance in operation, always correlating the activity of this subsystem to the behaviour of the UAV. The aircraft manufacturer wishes to implement the tool chain assessed during last years, to perform a heterogeneous simulation, able to show the customer both a functional and a physical simulation of the system response to some selected flight conditions. The tool chain includes the IBM Doors Next Generation® (DNG), for the requirements management, and the IBM Rhapsody®, for the functional modelling. The Harmony® approach is applied, according to the process model described by the "V-diagram" [5]. The IBM Design Manager® is used to manage the project, within the frame of the IBM Jazz® platform, aimed at managing the collaborative work of all of team operators, and to assure the complete traceability of system development. The Siemens Simcenter Amesim® is exploited for the multi-physics simulation of the system behaviour and to predict its performance. Therefore, a requirement to develop the MBSE process in this context is setting up a procedure of heterogeneous simulation which exploits the above mentioned tool chain, and enhances the capability of trade-off between technologies of the ECS. Because of the sensible content of information the access to the tool chain must be secure and authorized only to selected operators.

IV. SYSTEM DEVELOPMENT

The practice of the MBSE is nowadays very well known [3], therefore following sections are aimed to highlight some benefits and some crucial issues related to the application to the UAV system, while showing the steps of product development. It is a safety-critical system, since it is unmanned, therefore the operation control is a key design task. It is also a security-critical system, because it is used for some strategic actions, whose content must be preserved by any fraudulent attack and manipulation, as well as all the data used and stored must be protected. A flowchart of the MBSE process here applied is proposed in Fig.3. As usual, the system is developed by level, starting from the aircraft and going down to subsystems and components. The main activities are coloured, while some partial and digital products are highlighted on the left side by a dashed line contour. The SysML language is exploited, by using its diagrams (D).

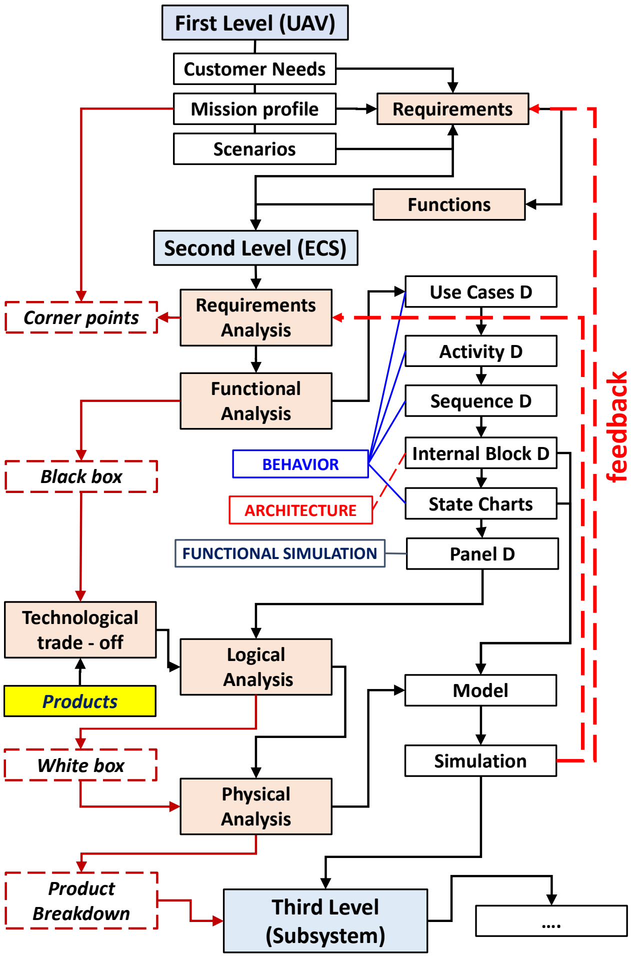

Fig. 3. The MBSE process used to develop the ECS system (draft).

A. *Mission: decomposing the complexity of scenarios*

A first benefit of resorting to the MBSE is appreciated when the mission and scenarios of the UAV are defined. The roles of UAV are multiple, as they include the so-called "dull" long term surveillance, the "dirty" monitoring of sites, under nuclear or chemical contamination, the "dangerous" inspection of strategic targets, the "covert" mission, in stealth configuration, the "research" development of innovative products, and the "environmentally critical" operation, aimed at exploring small populated areas [1]. For each scenario, a functional model can be set up, and its performance can be evaluated, by decomposing the complexity due to superposition of many functions, in an unique system. This is done at the first level of modelling. In addition, some specific scenarios can be defined, at second level, in terms of "corner points", i.e. the worst working cases. They are listed in Table 1, as they were defined by the manufacturer. The null altitude corresponds to ground. Three operational degrees are defined as "extremely, intermediate and regular (omitted)", either in hot or cold thermal condition.

TABLE I. CORNER POINTS FOR THE ECS OPERATION

Case	Condition	Altitude	Temperature	Air speed	Solar heat load	Avionics bay heat loads
		ft	°C	Mach	Watt/m^2	Watt
1	Ext. Hot	0	+50	0,00	1120	4792
2	Inter. Hot	0	+40	0,00	1120	4792
3	Hot	0	+37	0,00	1120	4792
4	Ext. Cold	0	-48	0,00	0	4792
5	Inter. Cold	0	-34	0,00	0	4792
6	Ext. Cold	46000	-72	0,55	0	1500
7	Ext. Hot	3000	+40	0,15	1120	6954

Case 7 describes a severe long endurance operating condition, typical of UAVs, corresponding to a sort of proof test. It consists in a flight at low altitude and low engine power level, in a hot environment, sunny day, and intensive activity of avionics. Those are limit conditions for heating, as a reduced availability of cooling air merges the highest heat generation in the avionics bay.

B. Requirement analysis: security management

A straight implementation of the MBSE is performed in the ECS development, by starting from the requirements elicitation at different levels, and introducing them through the requirement manager tool DNG® in the digital model. It allows overcoming the gap between Word® documents (document based) or IBM Doors® files (model based) and the functional model developed in the IBM Rhapsody®. Instead of importing the content of those files, the DNG® allows saving the requirements into a protected database, stored in a secure server, made accessible only to authorized users, via web. The requirements are automatically visualized within the IBM Rhapsody® to perform the functional modelling. Distinguishing requirements into different classes help the design activity, especially when the allocation is performed. In the ECS, separating the health monitoring and the thermal control, for instance, allows refining both the operational and architectural requirements. Some constraints define the operational requirements, as the temperature range of avionics, to be kept between –46°C and +71°C, the volume and shape of the avionic bay, completely defined by the manufacturer, as a prismatic box, whose cross section is rectangular in the rear part, and trapezoidal in the frontal one, with given dimensions, covered by a nondisclosure restriction.

C. Functional analysis: definition of a blackbox

Resorting to the SysML language, implemented within the IBM Rhapsody®, allows representing several behavior diagrams like the Use Case (UCD) in Fig.4. It allows realizing that stakeholders are more than those predicted by a common user. Particularly, the Utility Management and the Central Maintenance Systems interact one to each other, as the health monitoring activity is performed. Among the Use Cases, the air filtering is crucial and requires to be considered specifically. The ECS behaviour is analysed by implementing the practice of manufacturer in terms of diagrams usually drawn. The IBM Harmony© methodology is applied [3]. The Activity Diagrams (AD) are first developed, for each use case, to characterize not only actions, but even design parameters and guard values exploited to define the occurrence of each event, based on a triggering. The actors involved in each step are visualized (Fig.5). This makes easier the development of both the Sequence Diagram (SD), where actions performed by the actors are depicted, as a function of time (vertical line), and of the State Machine diagram (SMD), or Statechart, where the subjective point of view of the ECS is described. It shows the states reached by the system in operation, and the events causing each state change. The SMD is the core of functional simulation, being a first task of the heterogeneous simulation. It is animated automatically, by the IBM Rhapsody®. Each state is automatically explored, in sequence, by the tool, which sets up each trigger, to activate the events between states (Fig.6).

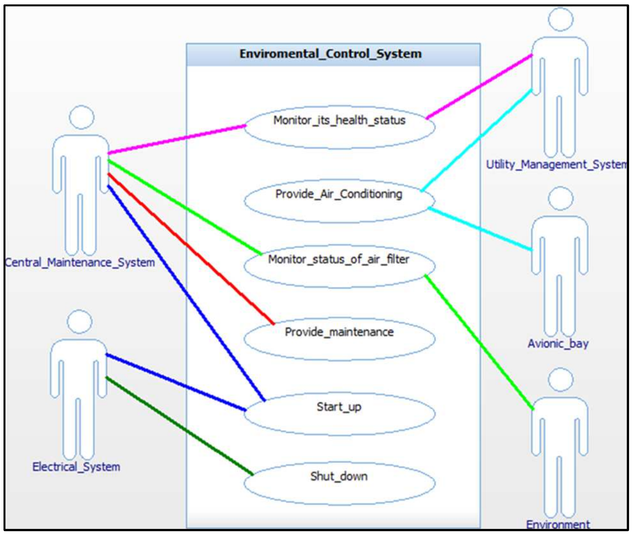

Fig. 4. The SysML Use Case diagram of the ECS.

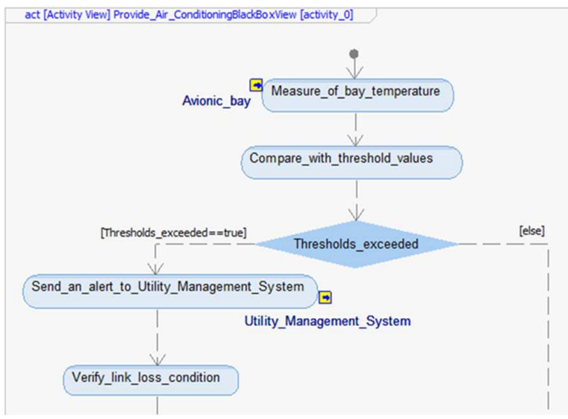

Fig. 5. Detail of the Activity diagram of the ECS, for the UC "Provide Air Conditioning" with actors (arrows) and thresholds.

The functional analysis provides a first outcome consisting of a Functional Breakdown Structure (FBS), which includes only functions, to be allocated to logical blocks first, and then to product components. It looks like a “black-box”, since only the function performed is defined, while the real component exploited is not yet selected nor depicted.

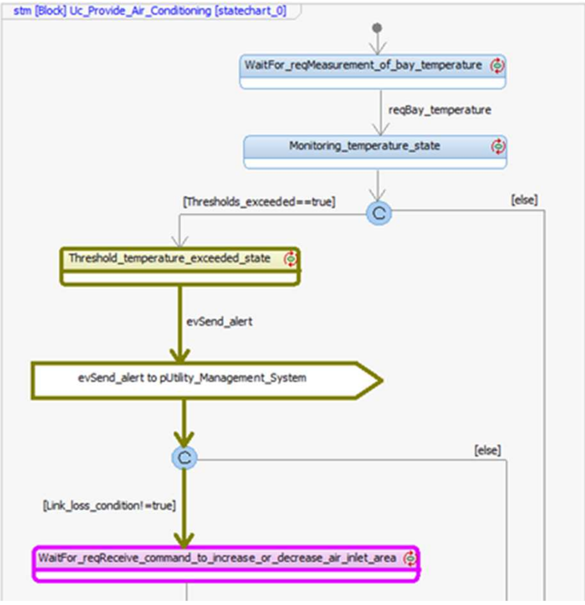

Fig. 6. Detail of the State Machine diagram of the ECS, animations are highlighted with bold lines and bright colours.

D. *Logical analysis: technological input*

The logical analysis is carried out after the functional one, to define the blocks, which allocate the system functions, and to describe the system architecture. In this case, a sort of “white-box” is defined, where not only the functions, but even the system components which allow exploiting them are disclosed. For the UAV, a screening of available technologies to design the ECS is performed starting from patents. In the tool chain the Espacenet® is linked to explore all the patents related to the ECS. This screening identifies some interesting patents, as the US3824598 [6] (Container with liquid to preserve electronic equipment from heating into a bay), the US6938679 [7], about the vapour cycle cooling system, the US10029808 [8] about the heat dispersion through the structure, and the US8602088 [9], on the air cooling system. To perform the trade-off of technologies, some typical metrics are suggested by the industrial practice (fractional influence on the evaluation), as the system performance (0.25), weight (0.1), volume (0.1), power consumption (0.1), maintainability (0.1), reliability (0.1), environmental impact (0.1), life (0.1), and the current state of their technological assessment (0.05). Surprisingly, as the performance of products described in those patents is calculated, as the sum of product between the fractional influence of each item and the mark assigned by their qualitative evaluation, the scores obtained are so close that differences are negligible, and a clear trade-off cannot be accomplished. A coupled functional and physical modelling is strictly required. Since the technology patented in the US6938679 exhibits the highest score, it is used as a reference to describe the corresponding IBD, although some other ones are even considered. Particularly, the competition between Air Cycle Cooling and Vapour Cycle Cooling Systems looks the most significant task.

E. *Physical analysis: size model and dynamic simluation*

Previous analyses highlight a double need to proceed with the product development. A prediction of some values like the temperature of the avionic bay wall (or skin), and the heat produced by the avionic systems, for given operating condition, is required to select the size of components. A numerical simulator predicts then the dynamic behavior of the ECS, even in transient response, if needed, as for instance in the Amesim® tool.

V. Numerical Modeling

A. *Size model: analytical approach*

To define some main properties of the two solutions proposed, a preliminary model is developed, based on analytical formulas. The skin temperature, T_w, of the avionic bay is calculated in flight as:

$$\mathbf{T_w} = \mathbf{T_0}\left[\mathbf{1} + \mathbf{r}\left(\frac{\boldsymbol{\gamma}-\mathbf{1}}{\mathbf{2}}\right)\mathbf{M^2}\right] \tag{1}$$

where T_0 is the temperature related to flight altitude, r = 0.9 (recovery factor), γ = 1.4 (specific heat ratio), M is the Mach number. Eq.(1) allows realizing that at T_{01}(3000 ft), T_{w1}=41.3°C and at T_{02}(46000 ft), T_{w2}=-61.2C°. At ground level, where Mach number is null, only an energetic balance with convection, conduction and thermal radiation allows calculating the skin temperature, i.e. for T_{03}=-48 C°, T_{w3}=-15 C° and for T_{04}=50 C°, T_{w4}=66 C°. Once that the skin temperature is found, the thermal analysis of the bay can be performed. Some cases are considered, as the ground operation of the UAV without cooling, and with cooling applied by a fan, and the flight cruise, at constant altitude and speed, with cooling provided by air inlet or by the ECS. This model assumes as null some heat exchanges as between avionic bay and fuselage, between avionic subsystems located within the bay, by conduction through the fuselage skin, by radiation between avionics and inner volume of the bay. The main core of this model is the thermal balance of the inner volume of the avionic bay, where it is assumed that heat produced by the avionic equipment is transmitted by convection to the bay, by conduction through the fuselage skin, and by convection to the external environment. The convection phenomenon can be either natural or forced. The thermal equilibrium is expressed as:

$$\mathbf{Q_{EC}} + \mathbf{Q_K} = \dot{\boldsymbol{m}}\boldsymbol{c_P}(\boldsymbol{T_{out}} - \boldsymbol{T_{in}}) \tag{2}$$

In Eq.(2), Q_{EC} is the heat produced by the avionic equipment, at least when working at the 10% of power consumption, spanning from 1500 W at 14000 ft to 8270 W at ground level and 50°C. The heat exchanged through the fuselage with the external environment is:

$$\mathbf{Q_K} = \boldsymbol{AK}(\boldsymbol{T_{rec}} - \boldsymbol{T_{bay}}) \tag{3}$$

where A is the exchange area, T_{rec} is the outer environmental temperature and depends on T_0 and on the square value of Mach number, T_{bay} is the temperature inside the avionic bay and K is the heat exchange coefficient:

$$\boldsymbol{K} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{h_{c\,out}}} + \frac{\mathbf{1}}{\mathbf{h_{c\,in}}} + \frac{\mathbf{L}}{\boldsymbol{\lambda}_{\mathbf{Mat}}}} \tag{4}$$

with

$$\boldsymbol{h_c} = \frac{\mathbf{Nu\,k}}{\mathbf{L}} \tag{5}$$

where k=0,028 W/mK, L=3,3855 m (length of the bay), Nu is the number of Nusselt [10], calculated in case of free and forced convection.

For the UAV operation at ground level, similarly the thermal equilibrium is evaluated. Without cooling it is assumed that the bay temperature is up to 140°C. A natural free convection is then established. The value of temperature inside the bay is then found, as:

$$\boldsymbol{T} = \boldsymbol{T_{bay}} + \left(\boldsymbol{T_{rec}} - \boldsymbol{T_{bay}}\right)\frac{\mathbf{1}}{\mathbf{e}^{\frac{\mathbf{KA}}{\boldsymbol{\rho} \mathbf{c_P} \mathbf{V}}\mathbf{t}}} \qquad (6)$$

where, assuming that T_{bay}=140°C, T_{rec}=50°C, i.e. is the maximum environmental temperature, product $\rho c_p V$ is the thermal inertia of air, when the 94% of the bay volume is exploited, and *t* is the instant at which the temperature is calculated. The result of this prediction is shown in Fig.7.

The meaning of "size model" is clearer when those numerical results are analysed. At ground level the system undergoes a very fast increasing of temperature, up to 71°C within 36 s. Since ground activities might need up to 30 minutes, a cooling system looks required even at ground level, not only in flight. Therefore the size of cooling system and its role in the ECS is defined. The simplest system to perform this activity is a fan, as for instance the Ametek Rotron Air Technology Products, MAXIAX 57515–AC (7.5 kg, 12000 rpm max, 840 l/s, 1456 W). It complies with some limitations of room applied to the fan system. If the bay is cooled by the fan, its temperature, predicted by the Eq.(6) looks like in Fig.8.

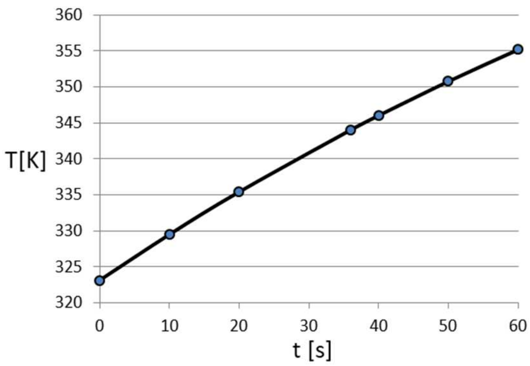

Fig. 7. Numerical prediction of the bay temperature performed by the size model.

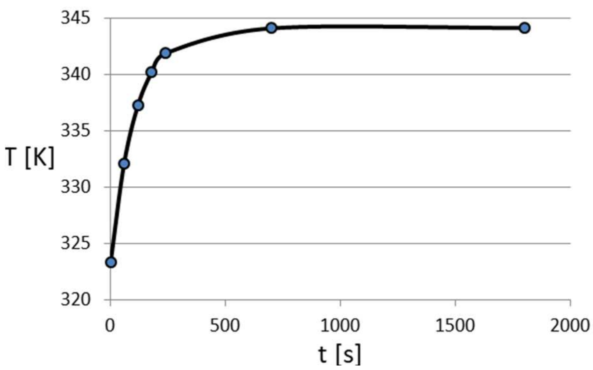

Fig. 8. Numerical prediction of the bay temperature performed by the size model when cooled by a fan.

It is remarkable that the avionic equipment work at a temperature lower than the upper limit of 71°C (345°K) for 700 s, therefore a temporal limitation to the ground activities might be added, if requirements about the fan size cannot be refined.

Two cases are analysed to predict the thermal conditioning in flight, corresponding to maximum and minimum temperatures. A forced convection is applied to the outer surface of fuselage, being cooled by the air flowing at the cruise speed of the UAV. A thermal conduction is applied to fuselage, while inside the bay a free convection is present. For the flight two scenarios are considered, namely the hot and the cold day, because the temperature dependency on the altitude is different. In a cold day at 46000 ft temperature is -46 °C, while in a hot day at 3000 ft temperature is +48°C. Air density and pressure are suitably predicted by a model of atmosphere [11]. The air speed is calculated by resorting to the flight envelope, which correlates altitude and true air speed [11]. The size model, in this case, is used to investigate whether in flight a simple air flow from an inlet in connection with the external environment might be sufficient to keep the temperature of the avionic bay within the range required. A requirement states that the maximum size of air intake is A= 25 cm^2. When the simulation of the thermal model previously discussed is launched by setting the data of flight, numerical results demonstrate that area is not sufficient. Moreover, to fit the requirement about the maximum temperature allowed, a larger cross section of the air inlet should be used, but the minimum temperature reached should be lower than -46°C in the coldest flight condition. Those limitations suggest to resort to a dynamic simulation to have a wider and deeper view of the system behaviour in presence of the ECS.

B. *Dynamic simulation and trade-off: numerical approach*

The Amesim® software tool is used to simulate the ECS performance. A preliminary functional model of the ECS, represented through an IBD, is exploited to create the numerical model. The Amesim® provides even a library of several common mechanical subsystems, which can be easily defined and characterized, through a list of typical parameters. Each element is fully defined, therefore for each set of inputs associated to air, the temperature of the avionic bay can be calculated. Basically, the thermal model expressed by the analytical approach is here replicated, but this numerical model analyzes the heat exchange between elements located within the avionic bay, and takes into account the properties of material constituting the structural skin (composite with carbon fibres). The whole model is described in Fig.9.

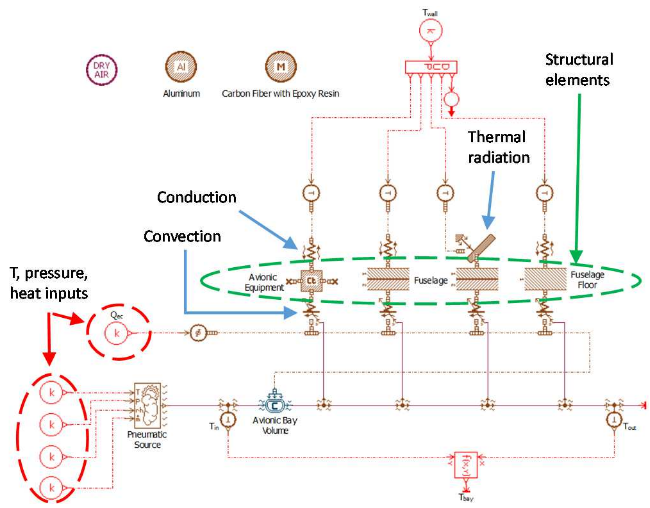

Fig. 9. Dynamic simulator of the bay thermal condition within the Amesim® tool.

A first simulation is used to check the numerical results of the analytical model. At ground level, with cooling system based on the fan, with air flow of 0.29 kg/s, for T_0=50°C and T_w=66°C the calculated T_{bay} is 68.3°C; for T_0=-48°C and T_w=-15°C the calculated T_{bay} is -29.6°C. In flight, with cooling effect induced by the air flow, T_{bay}= -55.77°C at 14021 ft, T_{bay}= 84.2°C at 914.4 ft. Those results confirm the need of the ECS to assure the fulfilment of thermal requirements in operation.

The Vapour Cycle Cooling System is sketched in Fig.10, and is based on a thermodynamic vapour cycle exploiting the two-phases cooling fluid R134a [12]. It starts as a vapour from the compressor, which increases its pressure and specific enthalpy. A condenser reduces the specific enthalpy of vapour, at constant pressure, and then vapour changes into liquid. The liquid passes through a valve, where pressure decreases, and then evaporation occurs, as the specific enthalpy rises up. The vapour is finally heated by the warm air of the avionic bay, and its pressure increases. The numerical model developed within the Amesim® tool allows calculating the temperature T_{in} of the air at the bay inlet, and at its outlet, T_{out}. Moreover, the temperature of the avionic bay is calculated if the model of the Vapour Cycle Cooling System is linked to that of the avionic bay as in Fig.9. The requirement satisfaction is easily verified if the "corner points" of the ECS operation are simulated and results are analysed as in Table 2. It includes altitude, skin temperature, pressure at the inlet of evaporator, temperature and pressure at the inlet of condenser, and temperature of the avionic bay.

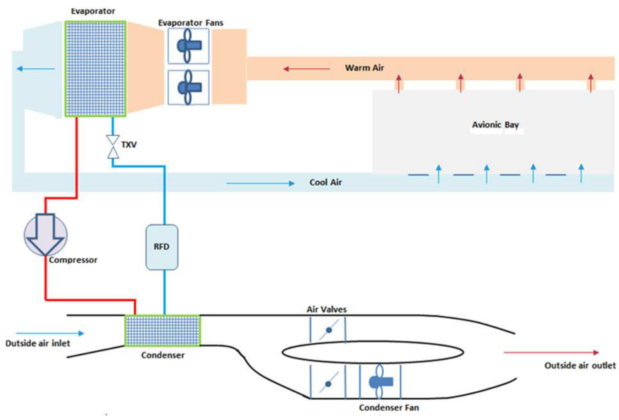

Fig. 10. Description of the Vapour Cycle Cooling System modelled.

TABLE II. MAIN RESULTS OF SIMULATION OF THE PHYSICAL MODEL OF VAPOUR CYCLE COOLING SYSTEM OPERATION

Altitude [ft]	T_w [°C]	$P_{IN,EVAP}$ [bar]	$T_{IN,COND}$ [°C]	$P_{IN,COND}$ [bar]	T_{BAY} [°C]
0	50	1.068	50	1,01	36,86
0	40	1.068	40	1,01	35,44
0	-34	1.068	-34	1,01	22,20
0	-48	1.068	-48	1,01	19
3000	41.3	1.080	41.3	1,09	54,30
46000	-61	0.680	-59	0,69	-27

The described solution allows satisfying all the operational requirements of the corner points. A deeper check is performed by simulating the whole flight mission composed by 18 steps, as is already available in the Amesim® library, section "Aeronautics and Space". Particularly, the simulator predicts the temperature profiles of T_{in}, T_{bay} and T_{out} along the flight mission, as a function of time (Fig.11). The flight mission includes some changes of altitude and of Mach number. Therefore, properties of the air entering the condenser change, together with the monitored temperatures.

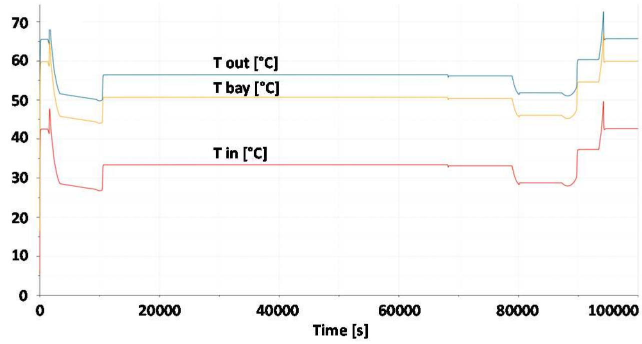

Fig. 11. Numerical simulation of temperature during the flight mission as performed by the Amesim® tool.

The Air Cycle Cooling System is modelled through the same software tool. Its layout is depicted in Fig.12.

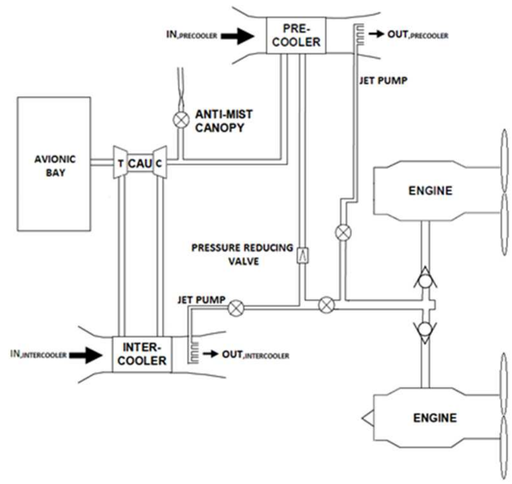

Fig. 12. Description of the Air Cycle Cooling System modelled.

The Amesim® model is connected to that of the avionic bay, like for the Vapour Cooling System. Therefore, the simulation evenly predicts the behaviour of the whole system. In this case, the numerical results related to the operational corner points are wore, as Table 3 shows, because temperature in the avionic bay exceeds the maximum allowed of 71°C.

TABLE III. MAIN RESULTS OF SIMULATION OF THE PHYSICAL MODEL OF AIR CYCLE COOLING SYSTEM OPERATION

Altitude[ft]	P_{bleed} [bar]	T_w [°C]	$T_{IN,PRE/INTERCOOLER}$ [°C]	T_{bay} [°C]
0	6	50	50	59.5
0	6	40	40	49.2
0	6	37	37	46.3
0	6	-34	-34	-9.5
0	6	-48	-48	-20.1
3000	15	41.3	41.3	90
46000	6	-61	-59	-32.1

The physical analysis points out that only the Vapour Cycle Cooling System satisfies the requirements allocated to this subsystem, and suggests to resort to this solution, by implementing its architecture, as a main result of the trade-off analysis.

VI. Design Synthesis

A. The white-box and functional simulation

The white-box describing the ECS system can be now drawn by resorting to a Block Definition Diagram (BDD), which includes the main components of the Vapour Cycle Cooling System, i.e. the ECS unit, sensors, control unit, filter and air conditioning system (Fig.13). The logical and physical analyses put in evidence the role of each element, by resorting to some "swimlanes" within the Sequence Diagrams (SD), which distinguish the actions performed by each actor/element by dedicating a specific column of their represented content (Fig.14). If the SD are drawn before the BBD, an automatic allocation allows recognizing the actors within the swimlanes and identifying them inside the BDD as in Fig.13.

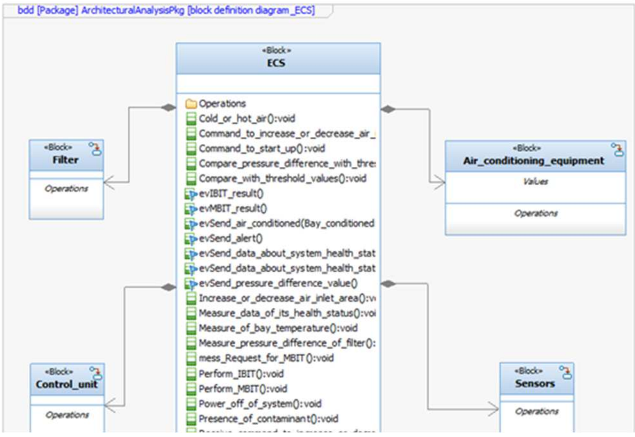

Fig. 13. Detail of a BDD of the ECS based on the Vapour Cycle Cooling System.

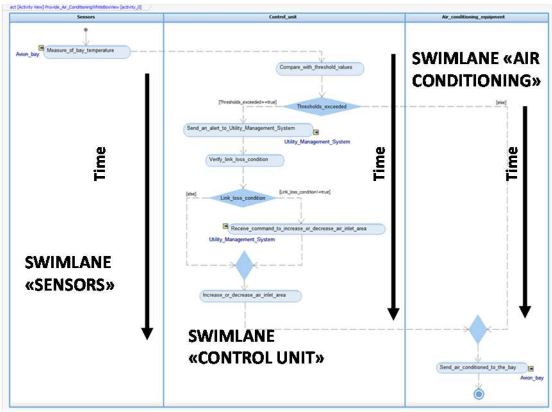

Fig. 14. Sequence Diagram (SD) with swimlanes describing the "whitebox".

From the SD drawn during the logical and physical analyses, with specified actors, the AD are generated as well as the new SMD, where functions are now allocated to components and the white-box is automatically implemented by the IBM Rhapsody® tool. This diagram can be exploited to build up a Panel Diagram, i.e. an intuitive interface for the customer aimed to allow verifying the requirements assessed (Fig.15). As is known, the panel diagram is used to animate the SMD as in Fig.6, or to perform the heterogeneous simulation, if it is directly interoperated with the dynamic simulator, as in present case happens with the avionic bay thermal model.

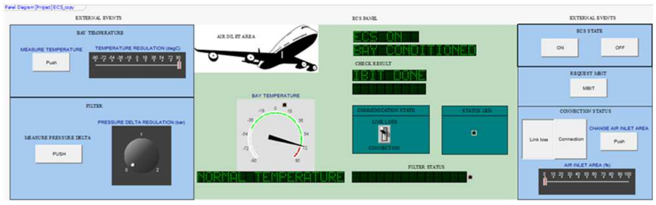

Fig. 15. Impression of the Panel Diagram for the functional simulation.

In the last case, an automatism similar to the creation of the SMD allows generating in the toolbox the BDD, from the AD and detailed Internal Block Diagrams (IBD), which are interoperated with the physical models, and often allow generating the physical model itself.

The Panel Diagram is a functional simulator, which can be used by the customer to validate needs. It allows debugging the functional model and checking its consistency as well as it helps in checking the complete allocation of requirements to functions and blocks, through the coverage feature [5]. Moreover, it allows testing the feeling of customer with the proposed solution. Some inputs are provided by the user as the bay temperature (target) and pressure, the state of ECS (on/off), and of communication (active/not), the air inlet area, while the simulator gives the bay temperature, for given boundary conditions, the states of functions and it warns about any anomalous behaviour of filtering, temperature and air conditioning.

B. The detailed architectural design

To define the details of design synthesis, the black-box SDs of all of Use Cases are updated and developed to become a white-box, where ports, interfaces, actors and activities are explicitly shown. Even the system architecture is defined. This activity is performed passing from the high level of system, or level one (L1) to subsystem level two (L2). This task greatly exploits benefits of the digital modelling. Once that a subsystem is selected, a revised version of the AD drawn at L1 is created, where actions are decomposed and allocated to subunits. In this procedure a strong contribution of swimlanes is appreciated, since they help in identifying the subunits (Fig.16) and the operations are allocated automatically by the software tool, to create the new BBD.

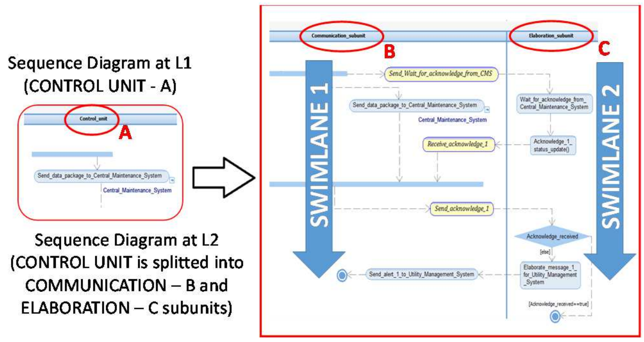

Fig. 16. SD deployed at higher level (L1) and subsystem level (L2) through an automatic selection of swimlanes.

The transition from system to subsystem includes the generation of detailed Internal Block Diagrams (IBDs), which are exploited to refine requirements, according to the subsystems layout. Finally, the creation of SMD is driven by the software tool, leading to a functional simulation.

VII. MODEL REUSE THROUGH MODULARITY

When a product line development is set-up, like in case of the UAV, an effective reuse of digital models from an assessed version to the newest one is recommended [13]. It reduces mistakes, cost, time to market and critical issues about safety and security. The reusability is a main goal of the MBSE. Very often the strategy of reuse is building a sort of product platform, which can be updated case by case. In the aerospace engineering, the reuse of digital models is performed by implementing a standard design process, as the ASD S1000D, which encourages to implement a modular design. The designer should define modules inside the system which allocate some defined functions, to be exported, saved and recalled by the new digital model, as a new product version is developed. Each module should be as independent as possible, capable to be tested separately, and characterized by some interfaces. These properties allow developing the modules separately, by different operators and shared only when integrated within the whole system. The design by modules is driven by the ASD S1000D, which describes even the Air Conditioning Equipment. Resorting to modules is associated to a careful management of the whole project, by a systematic approach as the MBSE, which exploits levels (L1, L2,..) to give a structure to the system layout. This is extremely useful in the Configuration Control Management, when some details are changed, to immediately realize the impact of each change.

The modular design is supported by libraries of elements, as in the Amesim® tool, which allows defining some "super-components", composed by linking and integrating several submodules. This approach is often applied in the dynamic simulators, but even in the functional modelling, when BDD and IBD are drawn. The MBSE helps in identifying the most suitable discretization of elements and the neighboroughs of each supercomponent, through a straight allocation of functions. The supercomponents allow simplifying the interface with the user, since in case of a sensitivity analysis, main design parameters are defined and updated by the user just by accessing to the supercomponent block. In the ECS, for instance, this strategy is applied to the thermal model of the avionic bay depicted in Fig.9, which is a supercompoment. It is then possible leading to a more compact representation of the whole system, as in Fig.17.

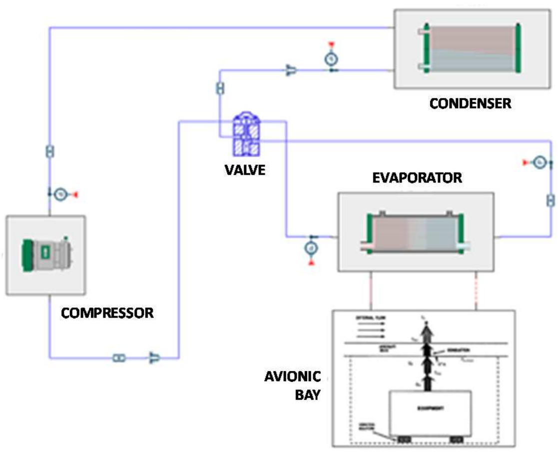

Fig. 17. Modular digital model of the ECS based on Vapour Cycle Cooling.

To enhance the reuse of this model, resorting to a process management via the Eclipse Process Framework Composer® (EPF®) is possible. It is used to create some digital libraries according to the SPEM (Software & Systems Process Engineering Meta-Model) methodology, which can be published and shared by the web in the HTML format. This option allows all the recognized users accessing and realizing the competences required by the product development, its tasks, the inputs and outputs of each activity and reading some outlines about the product manufacturing. This task is currently available in Leonardo Aircraft Division, as a sort of proof of concept, to be tested.

VIII. CONCLUSION

The novelty of the UAV makes its development rather difficult, without a clear driveline, which is provided by the MBSE. The functional modelling helps the designer in handling the complexity of the UAV roles and scenarios. The three typical analyses, namely functional, logical and physical, simplify the selection of system components, and of available technologies, during the trade-off. Only the heterogeneous simulation, integrating functional and numerical modelling, allows completing that task. Numerical simulation is performed by steps, a first sizing model figures out the system performance, for a preliminary check of requirements fulfilment. The dynamic simulation allows then refining both the system architecture and requirements. An effective reuse of digital models requires structuring the modelling activity by modules and levels, introducing super components and resorting to a process management.

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