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A SYSTEM INTEGRATOR'S PERSPECTIVE ON VEHICLE SYSTEM EVALUATION AT THE AIRCRAFT CONCEPT STAGE

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Abstract

Aircraft vehicle systems are the systems that enable an aircraft to fly safely. Function, performance, and other emergent properties of a vehicle system are impacted when it is integrated into an aircraft. Emergent properties of vehicle systems are used as criteria to evaluate them. Nowadays, vehicle systems are becoming more functionally-integrated. For an aircraft developer, predicting the emergent properties of a more functionally-integrated vehicle system might prove more challenging than predicting those of traditional, federated vehicle systems. This paper presents an approach that accounts for various aspects of an aircraft project that might impact an emergent property that the vehicle system is evaluated for. The approach is based on an analysis of data collected through a qualitative study conducted at Saab Aeronautics on the Gripen E/F aircraft project. The approach could enable vehicle system designers at the aircraft concept stage make more holistic predictions of the emergent properties of vehicle systems when they are integrated into an aircraft. The holistic approach could enable vehicle system designers anticipate undesirable emergence of a vehicle system at the aircraft concept stage. The undesirable emergence that could otherwise remain unanticipated until later in the life cycle of an aircraft.

Keywords: aircraft vehicle systems, aircraft concept stage, evaluation

1. Introduction

Aircraft developers are typically system integrators. They integrate an airframe with aircraft systems that they either develop themselves, contract vendors to develop or purchase commercial off the shelf (COTS) from vendors. Aircraft vehicle systems are the systems that enable an aircraft to fly safely [1]. In this paper, systems considered to be vehicle systems are the engine, environmental control system (ECS), fuel system, electrical power system, actuation system, and landing and braking systems. Nowadays, traditional, federated vehicle systems are being replaced by more functionally-integrated vehicle systems as noted in [2] and [3]. A more functionally-integrated vehicle system carries out functions that would usually be carried out by multiple traditional, federated vehicle systems. Aircraft are complex systems and the function, performance, and other emergent properties of a vehicle system are impacted when it is integrated into an aircraft. Emergent properties are used to evaluate a vehicle system concept. For an aircraft developer, predicting the emergent properties of a more functionally-integrated vehicle system might prove more challenging than predicting those of traditional, federated vehicle systems. This is because tacit knowledge and historical data for traditional, federated vehicle systems may be available at the aircraft developer. However, with the unavailability of data and knowledge for more functionally-integrated vehicle systems, the current evaluation approach might need to be improved. [4] used the generic life cycle model (ISO/IEC/IEEE 15288:2015) to define the life cycle of an aircraft and proposed that vehicle system design commence at the aircraft concept stage. If vehicle system concepts are generated at the aircraft concept stage then they should also be evaluated at the aircraft concept stage. Then the current evaluation approach should be improved to support vehicle system designers at the aircraft concept stage. Therefore, vehicle system designers could make more holistic predictions of the emergent properties of vehicle systems when they are integrated into an aircraft. Being able to make more holistic predictions at the aircraft concept stage can prove beneficial when integrating more functionally-integrated vehicle systems into the aircraft. Therefore, the purpose of this paper is to understand what aspects of an aircraft project impact the emergent properties of vehicle systems. To address this purpose, a qualitative study on the Gripen E/F aircraft project was conducted at Saab Aeronautics. The qualitative study and the analysis of the study that ensued, aimed at representing the perspective of the aircraft developer as a whole on vehicle system evaluation. Based on the analysis, an approach to vehicle system evaluation at the aircraft concept stage is presented in this paper. An approach that enables a vehicle system designer at the aircraft concept stage make more holistic predictions for the emergent properties of a vehicle system.

2. Emergence from a Complex System

To understand the emergence in complex systems, the distinction between complex and complicated systems made by [5] is adopted in this paper. In complicated systems, fixed relationships dictate the interactions between the many parts of the system. Complicated systems can be broken down into its constituent parts so that each part can be understood individually. These parts can be reassembled to understand the whole system. Therefore, complicated systems allow for reasonably reliable prediction of technical, time, and cost issues. On the other hand, parts of a complex system unlike those of a complicated system cannot be examined individually since the emergent properties of the system that are of interest disappear when the system is taken apart [5]. This distinction is analogous to an aircraft and its vehicle systems. From a system integrators perspective, an aircraft is a complex system and a vehicle system is a complicated system.

In an aircraft project, a vehicle system designer at an aircraft developer has to ensure that the chosen vehicle system architecture is feasible for the aircraft it has to be integrated into. When subsystems are integrated to create a complex system such as an aircraft, function and performance emerges from the system. Function being what the system does and performance being how well the system operates or executes the function. Performance is an attribute of the function of the system. Therefore, emergence is what appears when a system operates [6]. Functionality of a system emerges when the functions of the entities of the system, and their functional interactions combine. Therefore, functionality of the system is greater than its individual entities. The emergence of a system can be either anticipated or unanticipated. Both these types of emergence can be either desirable or undesirable. Desired anticipated emergence is linked to the desired outcome produced by the system – the primary function(s) the system is designed to perform [6]. The primary function of the fuel system of an aircraft is to transport fuel from the fuel tanks to the engine as well as re-distribute fuel between different tanks to maintain the center of gravity of the aircraft. The fuel tanks occupy large volumes of the airframe as shown in Figure 1 and large portions of the fuel tanks are exposed to the effects of the external environment due to the very thin skin of the airframe. Therefore, a desirable anticipated outcome from the fuel system is the use of fuel as a coolant for equipment that is warmer than it when the airframe skin and thus the fuel is exposed to cold ambient conditions. However, an undesirable anticipated outcome is when the airframe skin is exposed to warm ambient conditions that cause the skin temperature to increase. This in turn causes the fuel to get warm and the fuel may not be able to be used as a coolant. For both outcomes, the aircraft is performing its functions that result in the ambient conditions that the fuel is exposed to. Therefore, these outcomes emerged from the interaction between the functions of the aircraft and the function of the fuel system. The emergent performance of a vehicle system will be affected by its physical interfaces to other systems and equipment in the aircraft. Performance of a vehicle system may also be affected by systems or equipment placed in its vicinity in the aircraft. Therefore, the feasibility of a vehicle system is determined by its emergent properties that are impacted by its integration into the aircraft.

Function and performance are not the only inherent properties that emerge from a system. Other attributes of operation that emerge from a system include the various 'ilities' such as availability, maintainability, reliability, safety, robustness, and operability [6]. Affordability can also be an important property. In this paper, performance requirements and all the 'ilities' of the system will be referred to as the 'non-functional' requirements or constraints on the system. Therefore, when evaluating concepts of an aircraft vehicle system emergent properties other than function and performance must also be considered.

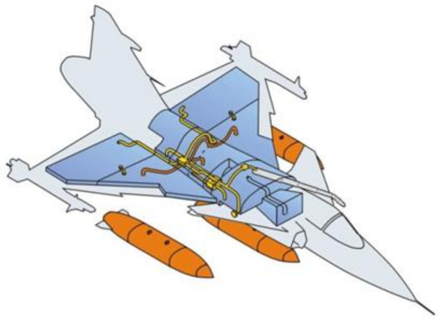

Figure 1 – Fuel tank configuration and location in the Gripen aircraft [7]

3. The Chosen Concept is a Compromise: The Integration of a Vehicle System into an Aircraft

The chosen concept of a vehicle system of an aircraft is a compromise that has to meet several constraints while also fulfilling functional requirements. Typically, the number of non-functional requirements is greater than the number of functional requirements on a vehicle system. The functional and performance requirements for an ECS of a manned fighter aircraft may include providing pressurized air within specific temperature ranges to various equipment or subsystems. However, the ECS would also have to fulfill several other constraints to be feasible for integration into the aircraft.

When evaluating vehicle system concepts, depending on the type of aircraft being designed some emergent properties might carry greater weighting than others. If ECS concepts being evaluated for a fighter aircraft are dependent on a bleed air supply then the concepts must account for thermal insulation of bleed air pipes. This is to protect neighboring fuel pipes and electrical harnesses against hot surfaces of the pipes due to high bleed air temperatures (> 200°C). However, the insulation would add to the total weight of the aircraft. Weight is a stringent constraint for a fighter aircraft since maneuverability is an essential capability of the aircraft. Then all concepts exceeding the weight threshold would be rejected. Aside from weight and volume constraints, another design and installation constraint for vehicle systems would be interchangeability. Vehicle system equipment would need to be interchangeable without requiring calibration or adjustment. Interchangeability and maintainability of a vehicle system would also be important factors in concept evaluation if low cost over the life cycle of an aircraft was a priority for the customer. Therefore, the emergent properties of interest when evaluating the system are driven by the type of aircraft being designed and the needs of the customer.

4. The Need for a Study of Vehicle System Evaluation at an Aircraft Developer

Functional integration of vehicle systems is increasing. It can be noted from [2] and [3] that there is clearly a shift from traditional federated vehicle systems to more functionally-integrated vehicle systems. The power thermal management system described in [2] is an integrated vehicle system that carries out the functions of an auxiliary power unit (APU), an emergency power unit (EPU), an ECS, and thermal management system. Therefore, predicting the emergent properties of more functionally-integrated vehicle systems when they are integrated into an aircraft might be more challenging than doing so for traditional, federated systems. When evaluating a vehicle system for an emergent property, all aspects from various design levels of an aircraft project that might impact that property must be considered. However, the evaluation of traditional, federated vehicle systems might rely more heavily on tacit knowledge and historical data at an aircraft developer. With the unavailability of historical data and tacit knowledge for evaluation of more functionally-integrated vehicle systems, a more holistic evaluation approach is needed. An approach that accounts for as many aspects of an aircraft project that might impact an emergent property that the vehicle system is evaluated for.

The emergent properties discussed in §2 and §3 are criteria for evaluating vehicle systems. At an aircraft developer, each of these criteria might be impacted by decisions or aspects at different design levels in an aircraft project. The number of design levels and the definition of a design level and what it entails might differ between aircraft projects within an aircraft developer or within the aeronautical industry. Some aircraft projects use a tier system where the customer needs are defined at the highest tier. This may be followed by aircraft design at the second tier, aircraft subsystem design at the third tier, and design of equipment of aircraft subsystems at the lowest tier. Hence, the purpose of this paper is to understand what aspects from different design levels of an aircraft project impact the emergent properties of vehicle systems. To address the purpose of this paper, a qualitative study on the Gripen E/F aircraft project was conducted at Saab Aeronautics. The qualitative study aimed at representing the perspective of the aircraft developer as a whole on vehicle system evaluation.

5. Methodology

The qualitative study on the Gripen E/F aircraft project was conducted using retrospective data-collection methods. The qualitative study was used to understand how the evaluation of a vehicle system is carried out at an aircraft developer. Typically, methods for a qualitative approach entail interviews, observation, and written documents, such as open-ended items on questionnaires and diaries [8, 9, 10].

5.1 A Qualitative Approach Using Retrospective Data-Collection Methods

Data-collection methods for design research can be classed into real-time methods and retrospective methods, indicating whether the methods are applied during events or following the events of interest [11]. For collecting data on the vehicle system evaluation process, real-time methods were not a viable choice for this paper. This is because of the long lead times in aircraft development. Using ISO/IEC/IEEE 15288:2015 to define the life cycle of an aircraft, the concept and development stage of an aircraft can sometimes span over a decade and the research grant funding this study is limited to three years. Therefore, in this paper, retrospective methods were chosen to collect data. The scope of the data collection, how the data was collected, how the collected data was analyzed, and the limitations with the data analysis are described in §5.1.1, §5.1.2, and §5.1.3, and §5.1.4, respectively.

5.1.1 Scope of Data Collection

The vehicle system of interest in this study was limited to the ECS of a manned fighter aircraft. Retrospective data-collection methods for this study included collecting data from formal product and project documentation and semi-structured interviews with various engineers. Data collected through documentation was limited to system specification documents of the ECS of Gripen C/D and Gripen E/F. All semi-structured interviews were of the 'interview guide' type. According to [12], for this type of interview a list of questions prior to the interview are generated and then explored during the interview. However, this type of interview does not prescribe to the precise questions and allows for the same topics to be covered across all interviews. Data collection through semi-structured interviews was limited to six engineers from various levels of operations and various functional groups at Saab Aeronautics who worked on the Gripen E/F project. The group of six engineers interviewed included an operational analysis engineer, two aircraft concept design engineers, two ECS-expert engineers, and one design and installation engineer.

5.1.2 Data Collection

Data collected from the ECS specification documents entailed noting the technical aspects of all major components of the ECS. The interviews with the six engineers were not conducted in any specific order reflecting the organizational structure of Saab Aeronautics. The interviews were scheduled around the availability of the engineers. Interviews with each of the six engineers were conducted separately. Semi-structured interviewing entailed common questions all six engineers were asked. However, with each interview further questions specific to each functional group the engineer belonged to ensued from the first author. All interviews were conducted in an informal discussion format and no audio recordings were made. All interviews were conducted by the first author. In addition, note taking during each interview was carried out by the first author. Following the interview, the first author reviewed the notes, wrote personal reflections, and then discussed the notes and reflections with the second author. The common questions for all engineers interviewed were as follows:

- What was your role during the development of Gripen E/F?
- What were your tasks in your role during the development of Gripen E/F?
- What factors and/or circumstances external to your respective functional group affected your tasks?

5.1.3 Data Analysis

The data collected through the various means described in §5.1.2 was merged and synthesized to describe how aspects of design in an aircraft project impact the emergent properties of vehicle systems. Various design levels of an aircraft project and their impact on emergent properties of vehicle systems is described in §6. Based on the analysis in §6, an approach to vehicle system evaluation at the aircraft concept stage is presented in §7.

5.1.4 Limitations with Data Analysis

Bias may arise when interpreting or analyzing data in qualitative research. [13] lists three archetypical sources of bias that occur in interpretation of data in qualitative research, namely the holistic fallacy, elite bias, and going native. Of these three types, going native pertains to the analysis of data in this paper. According to [13], going native entails losing one's perspective and being co-opted into the perceptions and explanations of local informants. This paper is intended to reflect the perspective of the aircraft developer on vehicle system evaluation at the aircraft concept stage. To reflect this perspective, data is collected from engineers from various functional groups. However, the data is analyzed by the authors and both authors of this paper belong to the functional group called 'Aircraft Vehicle Systems Methods, Modelling, and Simulation' at Saab Aeronautics. Therefore, the perspective presented in this paper may be biased towards that of a vehicle system engineer. It may not unbiasedly represent the perspective of the aircraft developer as a whole.

6. The Impact of Various Levels of Design in an Aircraft Project on Emergent Properties of Vehicle Systems

Properties that emerge when vehicle systems are integrated into an aircraft may be impacted by various levels of design in an aircraft project. Using the collected data, aspects from four levels of design in an aircraft project that impact the emergent properties of a vehicle system are addressed in this paper. From the highest level to the lowest level in an aircraft project, the four design levels considered in this paper are the 'operational level', 'aircraft level', 'subsystem level', and 'component level'. The four design levels that are considered in this paper are described in §6.1. The vehicle system of interest when collecting data was limited to the ECS of a manned fighter aircraft as stated in §5.1.1. Aspects from these four design levels that impact the ECS at hand are pictorially depicted in Figure 2 and the impact of these aspects on the emergent properties of the ECS is described in detail in §6.2.

As done in [4], a vehicle system architecture is defined as the pictorial layout of the relationships between the components of the system and the operands of the system. The operands being the thing the function changes. For the ECS case study in this paper, the operand is air and the ECS is dependent on air from the engine and the APU to operate. The architecture for the ECS case study is shown under the component level in Figure 2.

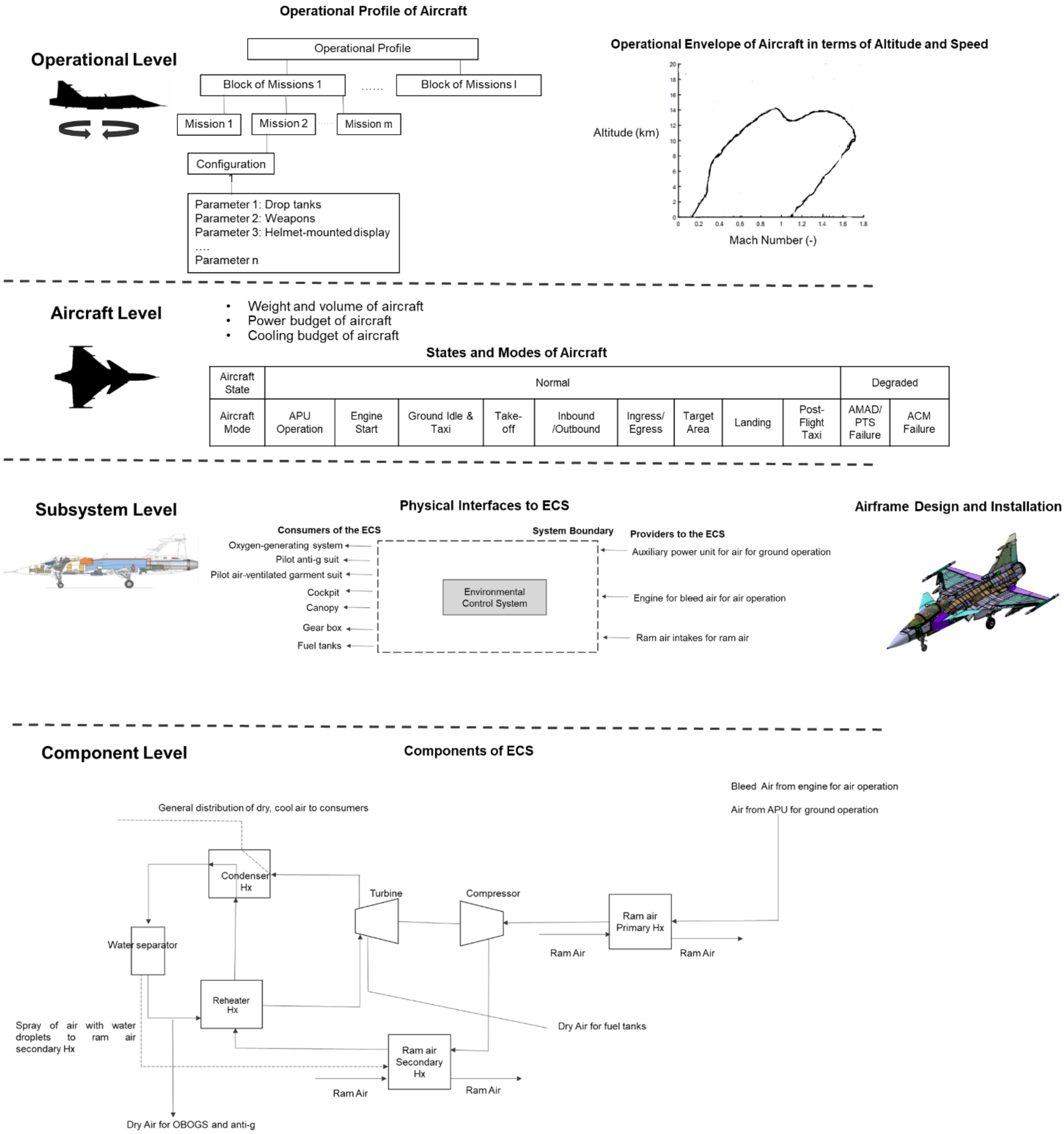

Figure 2 Aspects from four design levels of an aircraft project, namely operational, aircraft, subsystem, and component that impact the emergent properties of the ECS case study in this paper.

6.1 Description of Four Design Levels of an Aircraft Project

The four design levels considered in this paper, namely, operational, aircraft, subsystem, and component are described in §6.1.1, §6.1.2, §6.1.3, and §6.1.4, respectively.

6.1.1 Operational Level

In this paper, the highest design level in an aircraft project is defined as the operational level as shown in Figure 2. At this level, the operational profile of an aircraft is defined. The operational profile of an aircraft defines what the aircraft will be used for and how the aircraft will be used during its service life. The operational profile entails all 'l' number of blocks of missions an aircraft will fly as shown in Figure 2. Each block of missions consists of 'm' number of missions, each mission has a configuration, and each configuration consists of 'n' number of parameters as shown in Figure 2. Using ISO/IEC/IEEE 15288:2015 to define the life cycle of an aircraft, then usually at the aircraft concept stage the complete operational profile of the aircraft is not defined. The operational profile at this stage usually consists of only a few essential missions and the complete profile is built up over the course of the aircraft concept stage and aircraft development stage. The essential missions are used for sizing aircraft systems and equipment for worst case scenarios. Defining the complete operational profile of an aircraft enables the conversion of operational usage of the aircraft to design data. Design data for aircraft vehicle systems usually entails the operational envelope of the aircraft. For example, the altitude and temperature envelope of an aircraft is one of the design drivers for the fuel system of an aircraft. Similarly, the altitude and speed envelope of an aircraft is a design driver for the ECS and such an envelope is shown under the operational level in Figure 2. This envelope is adapted from [14]. At the operational level, operational concept design creates operational requirements that are captured at the aircraft level.

6.1.2 Aircraft Level

The aircraft level is the next level proceeding the operational level as shown in Figure 2. Operational requirements, technical requirements, business requirements, standards, and regulations are collated at the aircraft level to define functions and characteristics of an aircraft. These functions and characteristics are used to generate concepts of aircraft and aircraft subsystems. At the aircraft concept stage, all requirements may not be defined. Therefore, at the aircraft level, the weight and volume of the aircraft and the power and cooling budgets of the aircraft are estimated at the aircraft concept stage. These estimates are improved through an iterative process over the concept and development stage of the aircraft. Safety requirements based on an initial functional hazard analysis of the aircraft are also considered. Concepts representing the layout of power flow between systems in the aircraft are generated at the aircraft level. In this paper, these layouts will be termed as 'layout of power flow between systems'. An example of such a layout is adapted from [15] and is shown in Figure 3. For each layout of interest, the functions and failures of systems in the layout are identified and those functions and failures are used to determine the state of the aircraft. In this paper, ISO/IEC/IEEE 24765 is adopted to differentiate between a state of a system and a mode of a system. According to ISO/IEC/IEEE 24765, a state can be a characterization of the system at a given time, the value of the variables defining the system, a condition to a behavior or a function, something that determines the set of functions that can be performed, and other meanings. In this paper, a state is defined as the overall condition of the system that determines the set of functions that can be performed by the system in that state. On the other hand, a mode is defined as a set of related features or functional capabilities of a product. For the layout in Figure 3, the functional capabilities of the aircraft are reflected in the aircraft modes in the normal state of the aircraft as shown under the aircraft level in Figure *2*. On the other hand, the failure of the airframe mounted accessory drive (AMAD) or the power transmission shaft (PTS) or the air cycle machine (ACM) results in an aircraft mode for a degraded state of the aircraft. There are two aircraft modes under the degraded state of the aircraft and all other aircraft modes are under the normal state of the aircraft as shown in Figure 2. Therefore, for each power flow layout of interest, the aircraft modes under each aircraft state are determined.

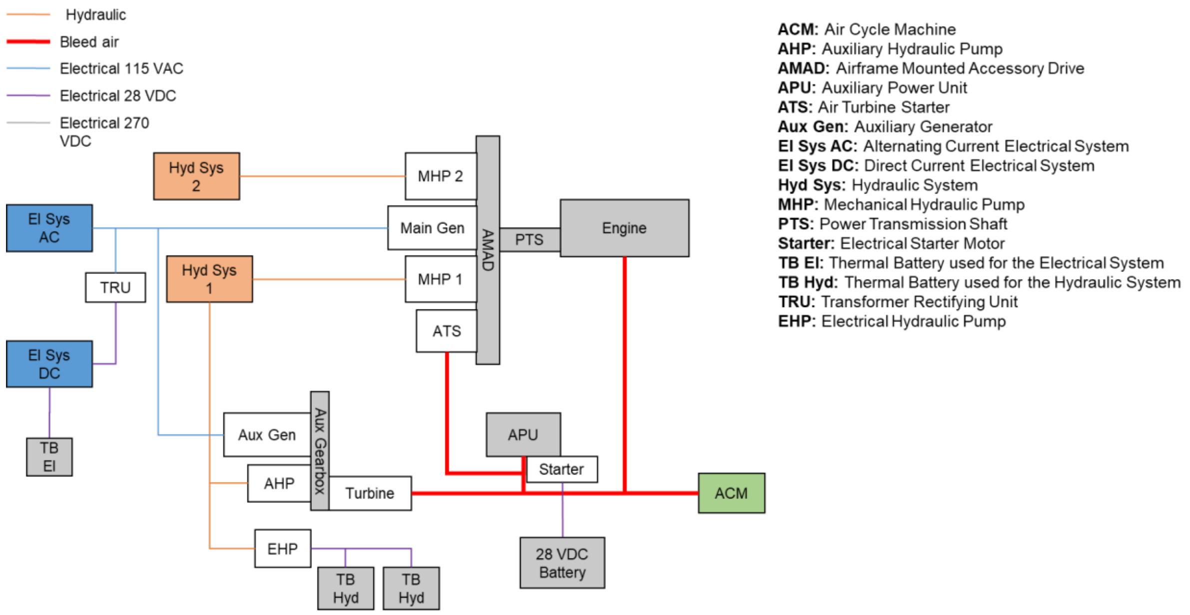

Figure 3 - A layout of power flow between systems of an aircraft [15]

6.1.3 Subsystem Level

At the subsystem level, at an aircraft developer vehicle system concepts are generated and evaluated, or COTS vehicle systems are evaluated. For the ECS case study, the systems that provide energy to the ECS and those that consume energy from the ECS are shown on either side of the ECS boundary under the subsystem level in Figure 2. This layout depicting the physical interfaces to the ECS is adapted from [4]. Vehicle system concepts are evaluated for their performance in various missions that the aircraft is designed to carry out. They are evaluated for their performance at specific points in the operational envelop of the aircraft. If an ECS concept depends on a ram air supply and venting system, then the concept is assessed for the drag it would add to the total drag of the aircraft due to the size of the inlets and outlets required for ram air. Vehicle system concepts would also be assessed for various 'ilities' mentioned in §2.

6.1.4 Component Level

At the component level, the components that a vehicle system concept consists of are considered. Vehicle system components are typically purchased COTS by the aircraft developer. Therefore, some emergent properties of vehicle systems like reliability and maintainability are obtained from the vendor.

6.2 Emergent Properties

From the collected data, it was noted that the emergent properties that a vehicle system are evaluated for are impacted by various levels of design in an aircraft project. For the design levels considered in this paper, their impact on the emergent function, emergent performance, and emergent safety of the ECS at hand are described in §6.2.1, §6.2.2, and §6.2.3, respectively and summarized in Table 1. These three criteria were chosen because unlike some of the other 'ilities', the collected data indicated that these three criteria are heavily impacted by aspects from the design levels considered in this paper.

Table 1 Aspects from the operational, aircraft, subsystem, and component design level of an aircraft project that impact the emergent function, emergent performance, and emergent safety of the ECS case study in this paper

		Aspects from Design Levels in an Aircraft Project			
		Operational Level	**Aircraft Level**	**Subsystem Level**	**Component Level**
Emergent Properties of the ECS case study in this paper	**Emergent Function of the ECS**	• Operation in hot, humid climate	• Aircraft modes • Aircraft Functions	• ECS providers • ECS consumers	• ECS components
	Emergent Performance of the ECS	• Altitude and speed envelope for aircraft • Missions flown by aircraft • Frequency of each mission	• Aircraft modes	• Surrounding equipment and/or systems	• Operating range of each ECS component
	Emergent Safety of the ECS	• Maneuvers performed in a mission	• Aircraft modes	• Operating ranges of ECS consumers • Monitoring and control of air to consumers Design and installation of airframe	• Probability of failure of each ECS component • Redundancies for monitoring and control of air

6.2.1 Emergent Function

Emergent function of the ECS at hand is impacted by operational requirements for the aircraft, functions of the aircraft, functions of the subsystems or equipment it is physically connected to, and functions of its components. At the operational level, the aircraft may need to fly in cool, dry climate as well in as hot, humid climate. In hot, humid climate, the water separator of the ECS may not function as well as it does in cool, dry climate. This in turn, can result in moist air entering the turbine that then results in ice build-up in the turbine. Therefore, if the turbine does not function properly then the ECS will not be able to carry out its cooling functions. As noted in §6.1.2, an ACM failure can lead to a degraded state of the aircraft. At the aircraft level, a set of functions the aircraft executes in a specific mode may influence the functions of the ECS in that mode. For example, the functions of the aircraft in take-off mode may interact with the functions of the ECS. The ECS has several consumers as shown in Figure 2 and the ECS may have to provide pressurized air to many of those consumers during take-off mode. Similarly, at the subsystem level, the function of a system that the ECS provides to or consumes from may interact with the functions of the ECS itself. The ECS at hand, requires bleed air from the engine to run. Therefore, functions of the engine may interact with the functions of the ECS. At the component level, the function of a component of a vehicle system is anticipated when the vehicle system concept is generated. However, the interaction between the functions of various components of the vehicle system must also be accounted for. The function of the primary heat exchanger of the ECS is to reduce the temperature of the bleed air to a certain threshold before it enters the compressor. The function of the heat exchanger may interact with that of the compressor and this in turn may influence the functions of the ECS. Therefore, to anticipate the emergent function of the ECS at hand, the climate the aircraft will operate in must be accounted for. The functional interactions between the ECS and the aircraft must be considered. Functional interactions between the ECS and its connected subsystems or equipment, and interactions between the components of the ECS, must also be considered.

6.2.2 Emergent Performance

Emergent performance of the ECS at hand is impacted by various aspects from different design levels of an aircraft project. At the operational level, the altitude and speed envelope of an aircraft as shown in Figure 2 is one of the drivers of the emergent performance of the ECS at hand. The emergent performance of the ECS may also be driven by the missions the aircraft is expected to carry out and the frequency of each mission. At the aircraft level, the performance of the aircraft in a certain mode may influence the emergent performance of a vehicle system in that mode. For example, during 'approach the target' mode, there might be a greater demand for pressurized air from the ECS than in other modes. Therefore, the emergent performance of the ECS may be impacted by the demand for pressurized air from the oxygen-generating system, pilot air-ventilated garment, and the pilot anti-g suit during this mode. At the subsystem level, the emergent performance of a vehicle system may be influenced by the equipment or other systems placed in its vicinity in the aircraft. For example, the performance of the condenser of the ECS may be influenced by the heat generation of equipment in its vicinity and thereby it would influence the emergent performance of the ECS. At the component level, if the components of the ECS are purchased COTS then each component will have an operating range it is designed to function within. Therefore, the inlet threshold temperature and pressure of each component will impact the emergent performance of the ECS. Therefore, the ECS at hand is impacted by aspects at all four design levels considered in this paper.

6.2.3 Emergent Safety

Similar to emergent function and emergent performance, emergent safety of the ECS is also impacted by various aspects of an aircraft project. At the operational level, the maneuvers the aircraft performs may impact the safety of the ECS at hand. The aircraft may need to carry out a steep dive close to the end of a mission when the fuel levels are usually low in the fuel tanks. This would require the ECS to provide the fuel tanks with air at a specific pressure during this maneuver to prevent fuel tank depressurization that could lead to an implosion of the tank. Similarly, at the aircraft level, the safety of the ECS is reflected in the example described in §6.2.2. When the aircraft is carrying out functions in a certain mode, a consumer(s) of the ECS may require the ECS to provide air at a specific temperature and pressure. The safety of the ECS that emerges is driven by the allowable probability of failure for the system. The probability of the ECS failing to provide to its consumers in a specific aircraft mode or when the aircraft is carrying out certain maneuvers must be kept as low as possible (typically less than ~10^-7) to prevent a catastrophic failure. At the subsystem level, the operating conditions of the consumers of the ECS may require the ECS to provide air to them within specified temperature and pressure ranges. In addition, at the subsystem level, the placement of functional sensors and valves for the ECS to monitor and control pressure, temperature, and flow rate of air are driven by the consumers of the ECS. For example, temperature and pressure sensors and temperature control and flow rate control valves would be placed along the piping between the ECS and the cockpit to monitor and control air from the ECS to the cockpit. At the subsystem level, the ECS is also impacted by the design and installation of the airframe. The ECS at hand depends on a bleed air supply from the engine and as noted in §3, thermal insulation of bleed air pipes is needed to shield neighboring wiring and piping against the hot surfaces of the pipes. Finally, at the component level, the probability of failure of each component of the ECS determines the emergent safety of the ECS. Further, at the component level, the emergent safety of the ECS is also determined by the redundancy for functional valves and sensors. Therefore, emergent safety of the ECS at hand will be impacted by aspects from all four design levels considered in this paper.

7. An Approach to Vehicle System Evaluation at the Aircraft Concept Stage

Emergent properties of vehicle systems are used to evaluate them. However, these emergent properties may be impacted by various aspects from different design levels of an aircraft project as noted in §6. Further, these aspects may not be defined or they may change over the course of the aircraft concept stage and this is noted in §6.1.1 and §6.1.2. For example, the operational profile impacts the ECS, however it evolves during the aircraft concept stage and aircraft development stage. The aircraft modes also impact the ECS and these modes may also change over the course of the aircraft concept stage. The aircraft modes are a result of the power flow layout of the aircraft. The power flow layout may evolve as the power and cooling budgets for the aircraft change and other requirements at the aircraft level change. Therefore, the evaluation of aircraft vehicle systems at the aircraft concept stage has to be recursive to account for changing aspects in the project that impact the emergent properties of vehicle systems.

Based on the data analysis presented in §6, a three-part approach to vehicle system evaluation at the aircraft concept stage is suggested. At the aircraft concept stage, firstly all the relevant design levels or tiers in the project should be identified. This information could be obtained through communication with the chief engineer of the project or the overall aircraft designer of the project. Secondly, aspects at each design level that might impact the emergent properties of the vehicle system should be accounted for as done in Table 1. Information about each design level can be obtained from the respective engineer(s) responsible for that level. Based on project requirements, all emergent properties of interest should be considered. Finally, using the information from the previous step, the impact of design aspects on an emergent property should be analyzed as done in §6.2.1, §6.2.2, and §6.2.3. In addition, analysis using system simulation tools could be used to support predictions of emergent performance of the vehicle system. This three-part approach could be employed recursively at the aircraft concept stage to account for changes in an aircraft project that impact the emergent properties of a vehicle system. The approach enables the vehicle system designer to evaluate the feasibility of a concept for the aircraft it is to be integrated into by making more holistic predictions for the emergent properties of the vehicle system. This holistic approach could enable vehicle system designers anticipate undesirable emergence of a vehicle system at the aircraft concept stage. The undesirable emergence that could otherwise remain unanticipated until later in the life cycle of an aircraft.

8. Concluding Remarks

Aircraft are complex systems and the function, performance, and other emergent properties of a vehicle system are impacted when it is integrated into an aircraft. Emergent properties of vehicle systems are used as criteria to evaluate them. Nowadays, vehicle systems are becoming more functionally-integrated. For an aircraft developer, predicting the emergent properties of a more functionally-integrated vehicle system might prove more challenging than predicting those of traditional, federated vehicle systems. An approach that accounts for various aspects of an aircraft project that might impact an emergent property that the vehicle system is evaluated for is presented in this paper. To demonstrate this approach, the aspects from four design levels of an aircraft project that impact the emergent properties of an ECS of a manned fighter aircraft are described. The number of design levels and what a design level entails might differ between aircraft projects within an aircraft developer or within the aeronautical industry. However, the approach presented in this paper can be employed to conduct a more comprehensive analysis of the aspects of an aircraft project that might impact an emergent property of a vehicle system. Therefore, this approach could enable vehicle system designers at the aircraft concept stage make more holistic predictions of the emergent properties of vehicle systems when they are integrated into an aircraft. In addition, vehicle system designers could use this approach to anticipate undesirable emergence of a vehicle system early in the life cycle of an aircraft.

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10. Copyright Statement

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