

MODELLING COUPLED ON-BOARD SYSTEMS IN AIRCRAFT DESIGN

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Abstract

Evaluating on-board systems in isolation, without accounting for their couplings and interactions, risks producing an unbalanced overall aircraft design. This study presents a method for modelling coupled aircraft on-board system architectures from a power management perspective and evaluating their complexity during conceptual design. A conventional and a more electric architecture are modelled in SysML v2, with on-board systems represented as interacting black boxes. Their power exchanges are captured using directed graphs and mapped using dependency structure matrices. The analysis shows that when compared to the conventional architecture, the more electric arrangement reduced the number of elements, redistributed power flows, and increased inter-system couplings. Nine complexity metrics were evaluated and produced differing assessments that resulted in a tie between the two architectures. In contrast, the weighted propagation cost metric captured the direction and propagation of cascading effects and indicated approximately 124% higher complexity for the more electric architecture. The study presents an approach in which logical architecture models can be combined with simple graph-based analysis to capture system interdependencies and evaluate architectural complexity. This supports the comparison of alternative on-board system architectures during aircraft conceptual design considering their couplings and interactions.

Keywords: Aircraft Conceptual Design, On-Board Systems, Complexity, Power Management, SysML v2

1. Introduction

Since the dawn of the jet age, five generations of fighter aircraft have shown drastic improvements in top-level performance and capabilities. Aside from revolutionary advances in avionics and mission systems, most improvements have been achieved through the incremental evolution of conventional on-board system architectures. Recent decades have seen the operational introduction of fundamentally different concepts, such as the More Electric Aircraft (MEA), which represents a paradigm shift that enables new energy sharing strategies. However, these architectures could present couplings that may induce emergent behaviours which, beyond their individual contribution, influence the top-level aircraft performance and could increase system complexity.

Despite advances in integrating on-board systems design into aircraft conceptual design, existing studies generally treat on-board systems independently, evaluating the overall architecture as the sum of their individual contributions. This neglects system couplings and the cascading effects they may generate, potentially giving rise to emergent behaviours that could lead to a less balanced architecture at the overall aircraft level.

The objective of this paper is to support the evaluation of candidate aircraft on-board system architectures during conceptual design by modelling them at the logical level, capturing power exchanges between systems, identifying couplings, and assessing their architectural complexity. Two fighter aircraft architectures, conventional and more electric, are used to illustrate the approach.

Rather than evaluating on-board systems in isolation, the proposed approach provides additional information by considering the complete arrangement of the coupled on-board system architecture, supporting architects in selecting the most promising configurations.

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2. Background

On-board systems are a set of interacting components, processes or functions connected together in an organized way that are combined to enable an aircraft to perform particular functions (Moir and Seabridge [1]). In tactical aircraft, on-board systems are expected to operate in extreme and harsh conditions while delivering maximum performance in a highly limited density-volume budget. In the search for maximizing energy, mass and volume usage efficiency, the MEA approach favours systems with higher levels of electrification searching to optimise overall aircraft power and thermal management, rather than addressing these functions independently at the subsystem level (Sprouse [2]).

While highly electrified aircraft architectures have been present in combat aircraft since the Vickers Valiant (whose only hydraulically actuated systems were the brakes and steering gear [3]), the MEA concept did not gain significant relevance until the introduction of Lockheed's F-22 Raptor in the 1990s. The trend was continued by the F-35 Lightning II, which further increased system integration through the use of power-by-wire Electrohydrostatic Actuators (EHAs) and a centralised Power and Thermal Management System (PTMS). These types of architectures are described in greater detail in previous work [4].

Emergent behaviours resulting from on-board system couplings of novel architectures have been reported in academia under various names, including systems interdependencies (Kuelper [5]), coupling effects (Delbeq [6]), function induction (Guenov [7], de Tenorio [8], Bussemaker [9]) among other terms and authors. Complexity analysis and the use of matrix methods in fighter aircraft on-board systems architecting has been presented in Drego [10] for thermal management systems and Krus [11] for power transformations in aircraft design. Of particular relevance is the mathematical description of these second-order effects given in Roelofs & Vos [12]. The authors state that the total System Characteristics (SC) are the product of both the sum of the individual contributions $f()$ of each Design Parameter (DP) plus a coupled term resulting from its interaction $f(DP1+DP2)$ as shown in Eqn. 1.

$$SC = f(DP_1) + f(DP_2) + f(DP_1 + DP_2) \tag{1}$$

The interaction term is defined as follows:

- $f(DP_1 + DP_2) > 0$: synergistic interaction;
- $f(DP_1 + DP_2) < 0$: discordant interaction.

Previous literature has typically evaluated candidate architectures by estimating how on-board system characteristics, such as system mass, power requirements, and drag, affect aircraft-level performance. These effects are usually combined through summations that assume interdependencies between systems. That is, the evaluation occurs vertically across system levels without first evaluating cascading effects within the same on-board system level (as proposed by Jünemann [13]) to capture "system-system" effects. As illustrated by the exploration axis in Fig. 1, the analysis first focuses on the interactions among on-board systems and then expands to the overall aircraft concept. For example, the use of power-density scaling (in kg/kW) to estimate individual systems mass ignores the fact that modifications may be required in other coupled systems to ensure functional requirements are fulfilled at the same levels. Failure to consider the extra components needed to reach the same level of system reliability could bias the predicted mass budget at the aircraft level.

This highlights the need for a modelling approach that explicitly captures the interactions between on-board systems. By representing the logical architecture and the power connections among its elements, the resulting couplings can be analysed to identify possible propagation of cascading effects across the aircraft.

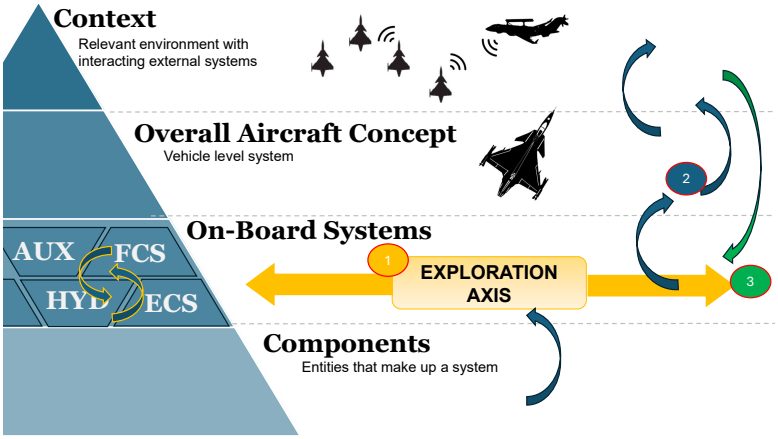


Figure 1 – An initial horizontal exploration of emergent behaviours between on-board systems is needed to later evaluate the total effects at higher system levels.

3. Methodology

In order to identify the most relevant interconnections and couplings between on-board systems, models of the logical architecture for given conventional and more electric architectures are presented. The model follows the Requirements-Functional-Logical-Physical (RFLP) methodology presented in Voth & Bertram [14]. From a given set of requirements, a functional architecture is derived whose functions are allocated to the interacting elements of a logical architecture that will eventually be realized by a physical system. These different representations correspond to the model "tenses" usage proposed in Axehill et al. [15].

The two architectures correspond to a conventional architecture typical of most 4th generation fighters and one with a centralised power and thermal management system such as the Lockheed F-35. The model is implemented in SysML v2 using Ansys' System Architecture Modeler (SAM) [16] and their corresponding structural views are shown in Fig. 2, where the top model represents the conventional architecture and the bottom model represents the MEA.

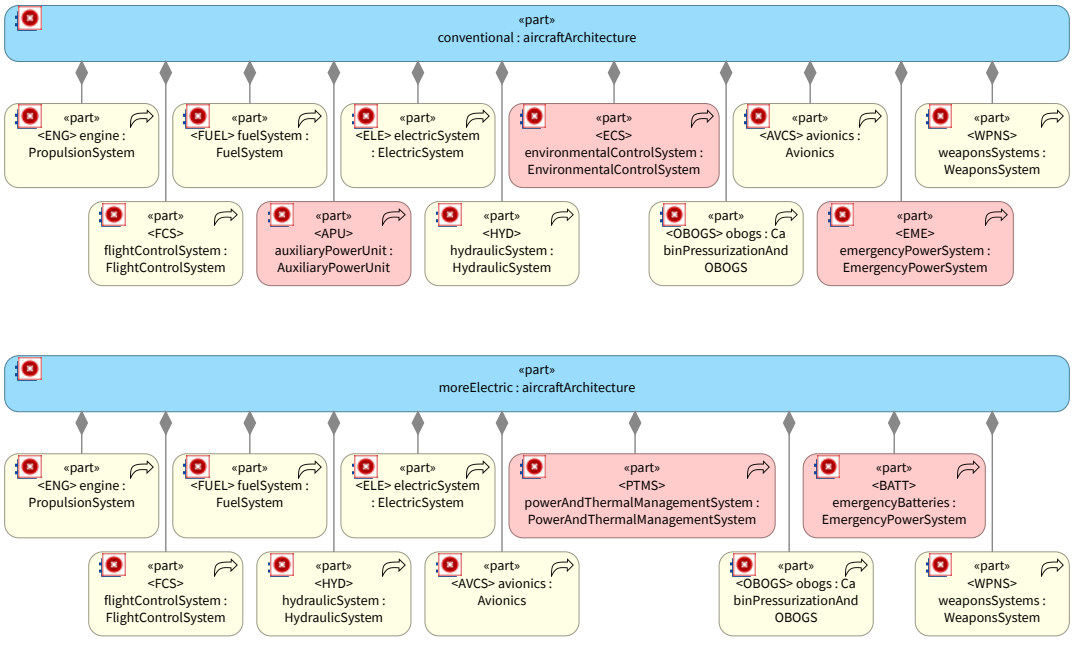


Figure 2 – SysML v2 representation of the conventional (top) and more electric (bottom) architectures used as examples

The textual representation of the SysML v2 model is used to abstract the architectures as directed graphs, as shown in Fig. 3. This representation enables the application of software- and graph-theory-inspired complexity metrics, as described in Sec. 3.4.

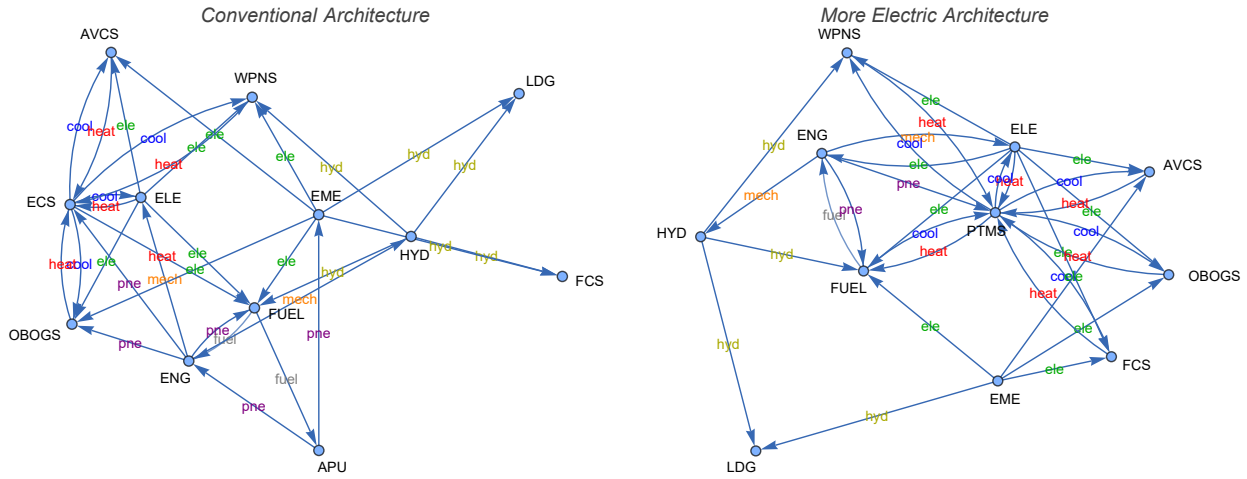


Figure 3 – Power exchanges between on-board systems for a conventional (left) and more electric (right) fighter aircraft architecture modelled as a directed graph

3.1 Logical System Architecture

Inspired by Staack [17] and Seabridge [18], a generic on-board system at the logical level can be abstracted as a black box possessing physical and non-physical attributes along with input and output ports as shown on the left of Fig. 4. Its implementation in SysML v2 as a part definition is shown on the right. These were specialized to the individual on-board system present in the aircraft, each one having their own input and output ports depending on the type of power exchanged. Although highly important, information exchange ports were not considered in order to focus solely on power exchanges.

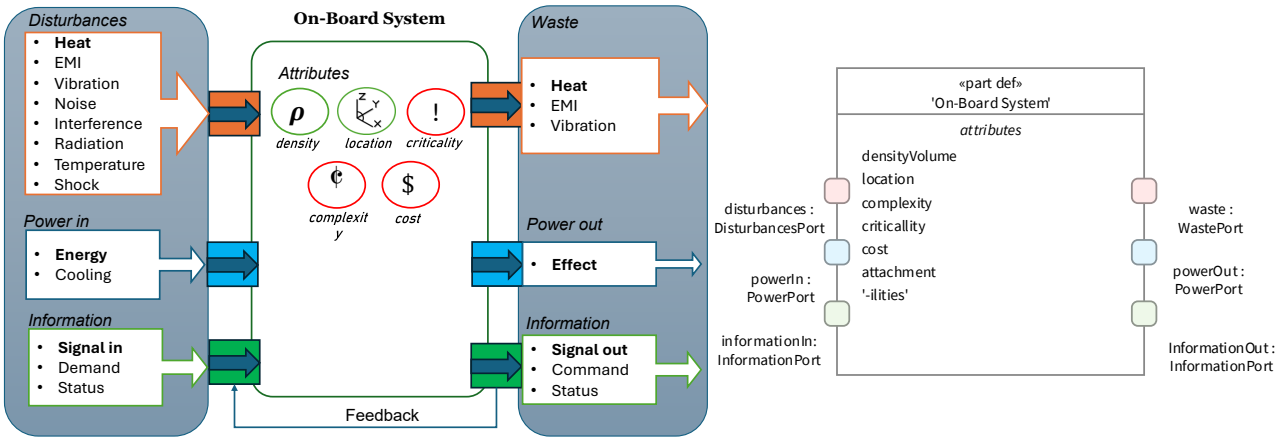


Figure 4 – Left: A generic on-board system black box model representation with inputs, attributes, and outputs. Right: Its implementation in SysML v2 as a part definition

3.2 Dependency Structure Matrix

For each architecture, a Dependency Structure Matrix (DSM) was then created. The DSM follows the Inputs in Rows / Feedback Above Diagonal convention (IR/FAD), where rows represent receiving systems and columns represent providing systems. The dependencies represented in these matrices can be interpreted as shown in Fig. 5, where on-board systems may operate in parallel (left), exchange power sequentially (middle), or exhibit coupled interactions (right).

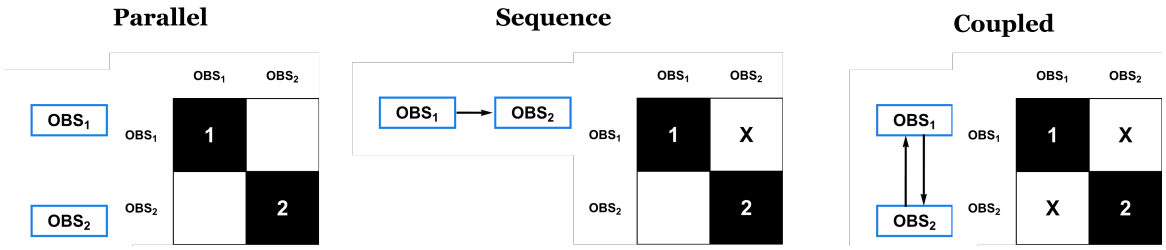


Figure 5 – Dependency Structure Matrix (DSM) showing on-board systems in parallel (left), sequential (middle) and coupled (right) relationships

3.3 Complexity metrics

The logical architecture models are evaluated using nine adapted complexity measures, from which the first four are described in Kinnunen [19]. The first metric is the Halstead difficulty (D_H) shown in Eqn. 2, which estimates the complexity associated with the diversity and frequency of power exchange interactions. m_{type} is the number of distinct power-exchange types (pneumatic, electric, etc.), n_{sys} is the number of distinct on-board systems, and n_{con} is the total number of power interconnections.

$$D_H = \left(\frac{m_{type}}{2}\right)\left(\frac{2\,n_{con}}{n_{sys}}\right) \tag{2}$$

The second metric is McCabe's cyclomatic complexity (v), defined in Eqn. 3. The same variables are used as before, with the addition of p, which represents the number of disconnected subnetworks. For a fully connected aircraft architecture, $p = 1$.

$$v = n_{con} - n_{sys} + p \tag{3}$$

Also called the fan-in and fan-out metric, the average total degree ($\bar{D}_{fan}$) measures the average number of power interconnections associated with each on-board system. It is given in Eqn. 4, where d_i is the total incoming and outgoing power interconnections associated with a single on-board system i. The metric is computed as the arithmetic mean of these values over all on-board systems.

$$\bar{D}_{fan} = \frac{1}{n_{sys}} \sum_{i=1}^{n_{sys}} d_i \tag{4}$$

Meyer's part counting method weights complexity based on the number of systems, system types, and interconnections within the architecture measured by a complexity factor (C_M). In Eqn. 5, m_{sys} is the number of distinct system types. For the level of abstraction considered in this work, each on-board system is treated as a distinct system type, such that $m_{sys} = n_{sys}$.

$$C_M = \left(n_{sys} \cdot m_{sys} \cdot n_{con}\right)^{1/3} \tag{5}$$

The Resource State Complexity (RSC) is an adaptation from the metric presented in Domerçant [20] and is given in Eqn. 6, where $H(x)$ is the entropy of the resource-state space and $\lambda(A)$ is the largest eigenvalue of the architecture's binary adjacency matrix (A). This matrix is derived from the aircraft DSM, with entries of 1 indicating an interconnection and 0 indicating its absence.

$$RSC = (\,1 + H(x)\,)\;\frac{\lambda(A)}{n_{sys} - 1} \tag{6}$$

The entropy of the resource-state space ($H(x)$) quantifies the diversity of power types exchanged through on-board system interconnections using the probability that a randomly selected interconnection exchanges power type k, where $n_{con,k}$ is the number of interconnections exchanging power type k (e.g., the number of interconnections exchanging pneumatic power). It is given by:

$$H(x) = -\sum_{k=1}^{m_{type}} \frac{n_{con,k}}{n_{con}} \log_2\left(\frac{n_{con,k}}{n_{con}}\right) \tag{7}$$

Also from Domerçant, an adaptation of the Resource Processing Complexity (RPC) metric is used to quantify the complexity associated with power transformations within the architecture. The RPC of system i is given in Eqn. 8. It multiplies the number of distinct power types received by the system ($|R_{in,i}|$), the number of distinct power types supplied by the system ($R_{out,i}$), and the number of distinct power types handled by the system ($|R_{in,i} \cup R_{out,i}|$). For architecture-level evaluation, the total sum of the RPC values of all on-board systems (RPC_{tot}) is used.

$$RPC_{\text{tot}} = \sum_{i=1}^{n_{\text{sys}}} \left(|R_{in,i}| \cdot |R_{out,i}| \cdot |R_{in,i} \cup R_{out,i}| \right) \tag{8}$$

Kuelper et al. [21] propose that the architecture complexity (C_K) can be estimated as the product of the number of on-board systems and the number of power interconnections. It is given by:

$$C_K = n_{sys} \cdot n_{con} \tag{9}$$

A simplified version of the overall systems level complexity metric (M_{OSC}) in [5] is presented in Eqn. 10. Here, $n_{con,i}$ is the number of power interconnections associated with system i, and m_{type} is the number of distinct power types exchanged within the whole architecture.

$$M_{OSC} = \left(\sum_{i=1}^{n_{sys}} n_{con,i} \right) \cdot m_{type} \tag{10}$$

A complexity metric inspired by Zeidner [22] accounts for differences in power-exchange complexity by assigning a weight (w_k) to each power type and multiplying it by the number of interconnections carrying that power type ($n_{con,k}$). The sum is then multiplied by the number of on-board systems (n_{sys}) as shown in Eqn. 11.

$$C_Z = n_{sys} \sum_{k=1}^{m_{type}} w_k \, n_{con,k} \tag{11}$$

The weights assigned to each power exchange type (w_k) are a subjective assessment of the relative complexity associated with the generation, distribution, and reception of each power type. The weights used in this study are the same as those used by Zeidner and are shown in Table 1.

Table 1 – Complexity weights assigned by Zeidner [22] to each power exchange type and also used here.

Power exchange type	Complexity weight (w_k)
Electrical (ele)	4
Pneumatic (pne)	1
Mechanical ($mech$)	5
Thermal ($heat$)	2
Fuel ($fuel$)	3
Hydraulic (hyd)	4
Cooling ($cool$)	1

3.4 The Weighted Propagation Cost metric

As can be seen from inspecting the previous metrics, none of them consider increasing complexity due to effect propagation. To account for this, the Weighted Propagation Cost (WPC) is proposed as a coupling-oriented complexity metric adapted from Benkoczi et al. [23]. It penalizes architectures where effects can spread through chains of power exchanges. The adjacency matrix A is converted into a weighted adjacency matrix (D) by assigning a complexity weight (w_k) corresponding to its power exchange type, as specified in Table 1 and resulting in a weighted propagation matrix (e^D) shown in Eqn. 12.

$$e^D = \sum_{l=0}^{\infty} \frac{D^l}{l!} \tag{12}$$

The matrix power l of the matrix corresponds to the number of consecutive power exchanges (edges) in a propagation path. For example, consider three arbitrary on-board systems A, B, and C with the following power exchanges

$$A \rightarrow B \quad , \quad B \rightarrow C$$

The corresponding weighted adjacency matrix is

$$D = \begin{bmatrix} 0 & w_{AB} & 0 \\ 0 & 0 & w_{BC} \\ 0 & 0 & 0 \end{bmatrix}$$

where w_{AB} and w_{BC} are the corresponding complexity weights associated with the power exchanges. The first matrix power $D^1 = D$ contains only direct propagation paths consisting of a single power exchange. So it only captures the direct exchange $A \rightarrow B$ but not the indirect $A \rightarrow C$.
However, the second matrix power ($D^2 = D \cdot D$) does contain all propagation paths composed of two consecutive power exchanges. In this example, the indirect propagation $A \rightarrow C$ corresponds to the matrix entry $(D^2)_{AC} = w_{AB} \cdot w_{BC}$ that appears in the following multiplication.

$$D^2 = D \cdot D = \begin{bmatrix} 0 & w_{AB} & 0 \\ 0 & 0 & w_{BC} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & w_{AB} & 0 \\ 0 & 0 & w_{BC} \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & w_{AB}w_{BC} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

This concept is extended to propagation paths of all lengths through the infinite summation in Eqn. 12. The term $l!$ progressively reduces the contribution of longer propagation paths, ensuring that direct and short-range interactions have a greater influence on the metric. The matrix exponential (e^D) is used because its Taylor series expansion

$$e^D = \sum_{l=0}^{\infty} \frac{D^l}{l!} = I + D + \frac{D^2}{2!} + \frac{D^3}{3!} + \cdots$$

naturally represents propagation paths of all lengths, with the factorial denominator already present, from Eqn. 12.
To obtain the WPC as a single architecture-level complexity metric, every entry of the weighted propagation matrix, $(e^D - I) \in \mathbb{R}^{n_{\text{sys}} \times n_{\text{sys}}}$, is summed. This operation is represented by the double summation in Eqn. 13. The identity matrix (I) is subtracted to remove the zeroth-order propagation term (that is, the first element of the Taylor series), ensuring that only propagation between distinct on-board systems contributes to the metric.

$$WPC = \sum_{i=1}^{n_{sys}} \sum_{j=1}^{n_{sys}} \left(e^D - I\right)_{ij} \tag{13}$$

4. Results

The results of the evaluation of the system logical architecture models are now presented. Figure 6 shows both Dependency Structure Matrices (DSM) for the conventional (upper) and more electric (lower) architectures. While the atmosphere (ATM) and the mission are not on-board system per se, these are shown to denote that they either influence the operating conditions of the systems or realize a specific function from the functional architecture (such as producing aircraft motion or providing mission capability). The italic and underlined elements denote that these are primary sources of energy (e. g., fuel or batteries).

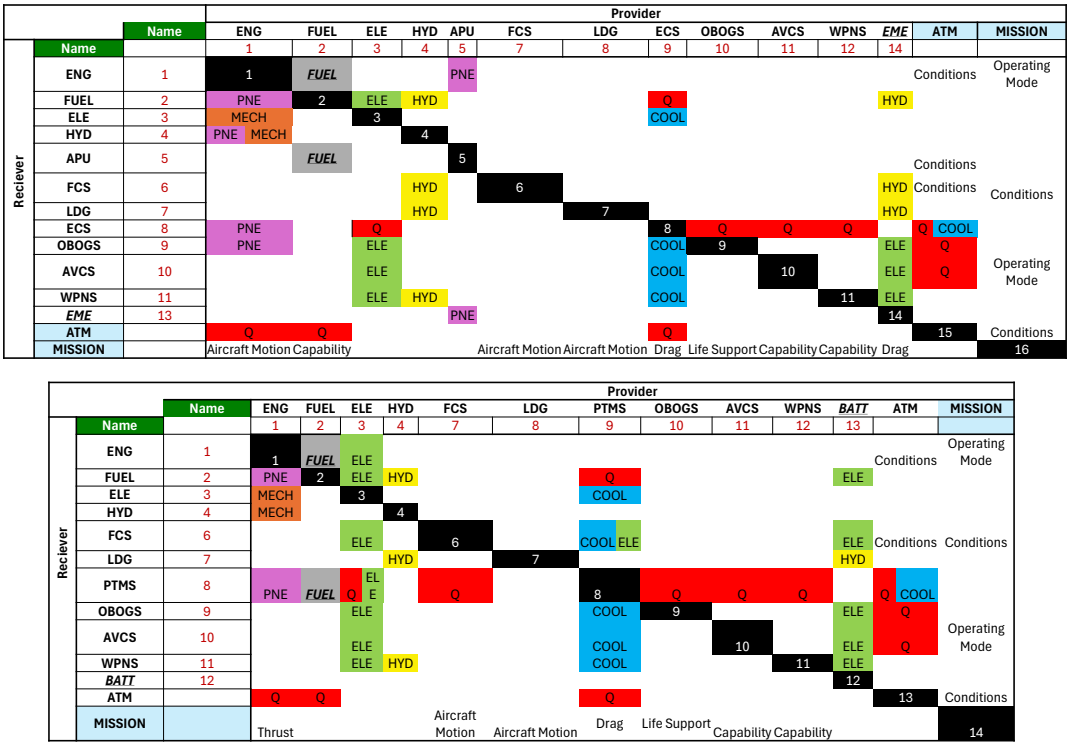


Figure 6 – Dependency Structure Matrix (DSM) for the conventional architecture (upper) and the more electric (lower)

The DSM shows that the more electric architecture has fewer system elements, as evidenced by having one less column and one less row. The Flight Control System (FCS) now exchanges electricity instead of hydraulic power and the Power and Thermal Management System (PTMS) performs the functions of the Environmental Control System (ECS), the Auxiliary Power Unit (APU) and the Emergency power system (EME) (reconfiguration of the PTMS would also allow for electric power to be provided to the FCS in case of emergencies [4]). A hydraulic system (HYD) is still present to provide auxiliary actuation and a battery (BATT) is used to handle transient loads and provide emergency electrical and hydraulic power.

Regarding system couplings, Fig. 7 shows that for the conventional architecture the most highly interconnected system is the ECS, all other systems have a single coupling. One coupling example is the engine (ENG) and fuel systems, where the latter supplies fuel while the ENG provides bleed air for fuel tank inerting and pressurization system. For the MEA architecture, the PTMS becomes the most highly interconnected system with six couplings. One example is the additional coupling with the fuel system because the PTMS can be reconfigured to operate as a combustor during emergencies. The introduction of the electrically driven Engine Starter/Generator (ES/G) also creates a new coupling between the ENG, FUEL, and ELE systems.

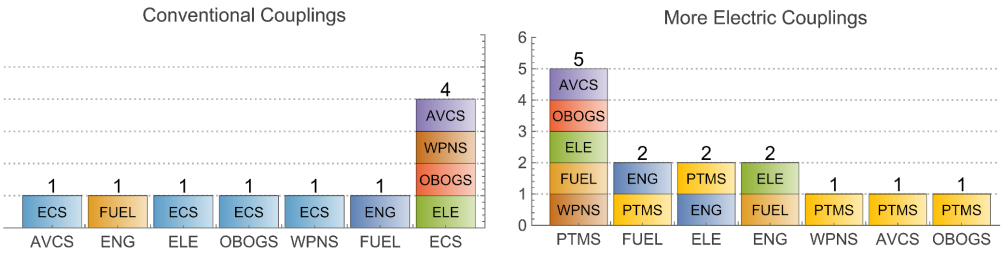


Figure 7 – Couplings between on-board systems (some systems are repeated for clarity)

Regarding the first nine complexity metrics of the logical level architectures, four indicated that the conventional architecture was more complex, one metric resulted in a tie (McCabe's cyclomatic complexity) and four others indicated that the more electric architecture was more complex. Results are shown in Table 2.

Table 2 – Comparison of architecture-level complexity metrics for the Conventional and More Electric Architectures (MEA). The larger value for each metric is highlighted in bold.

Metric	Symbol	Conventional	MEA
Halstead	D_H	18.7	**19.7**
McCabe	v	**21**	**21**
Fan-in Fan-out	$\bar{D}_{fan}$	5.3	**5.6**
Meyer	C_M	**16.6**	15.5
Kuelper	C_K	**384**	341
Domerçant RSC	RSC	0.92	**1.10**
Domerçant RPC	RPC_{tot}	100	**130**
Kuelper OSC	M_{OSC}	**448**	434
Zeidner	C_Z	**1092**	979

Since the complexity metrics are reported on different numerical scales, they are normalized with respect to the conventional architecture using $\Delta C = 100(C_{\text{MEA}} - C_{\text{Conv}})/C_{\text{Conv}}$.This allows a direct comparison of the relative differences between metrics, as shown in Fig. 8.

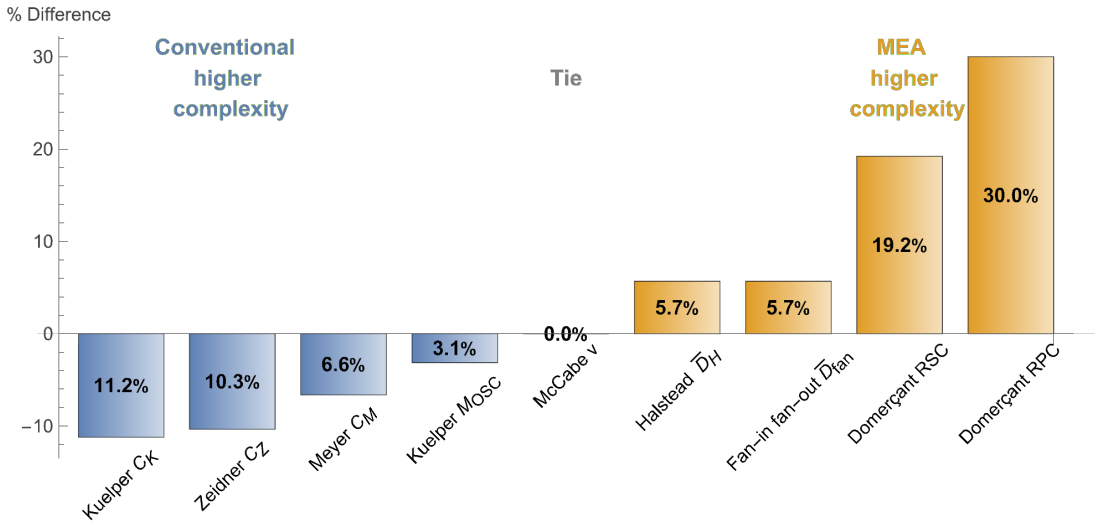


Figure 8 – Complexity metrics results comparison as percentage differences

The matrices used to compute the Weighted Propagation Cost (WPC) are shown in Fig. 9 for the conventional (upper) and more electric (lower) architectures. The weighted DSM (left) assigns a darker colour to interconnections associated with more complex power-exchange types. The propagation matrix (centre) represents the total influence of each on-board system by accounting for all direct and indirect power-interaction paths throughout the architecture. Finally, the bar charts (right) show the contribution of each on-board system to the overall WPC. The resulting metrics are

$$WPC_{\text{conv}} = 7{,}075 \qquad WPC_{\text{MEA}} = 15{,}845$$

These results indicate that the more electric architecture exhibits a 124% higher WPC than the conventional architecture. Inspection of the system contributions further shows that, in the MEA, the electrical system (ELE) becomes the largest contributor to the overall complexity, replacing the engine (ENG) because of its role as the central power-distribution system.

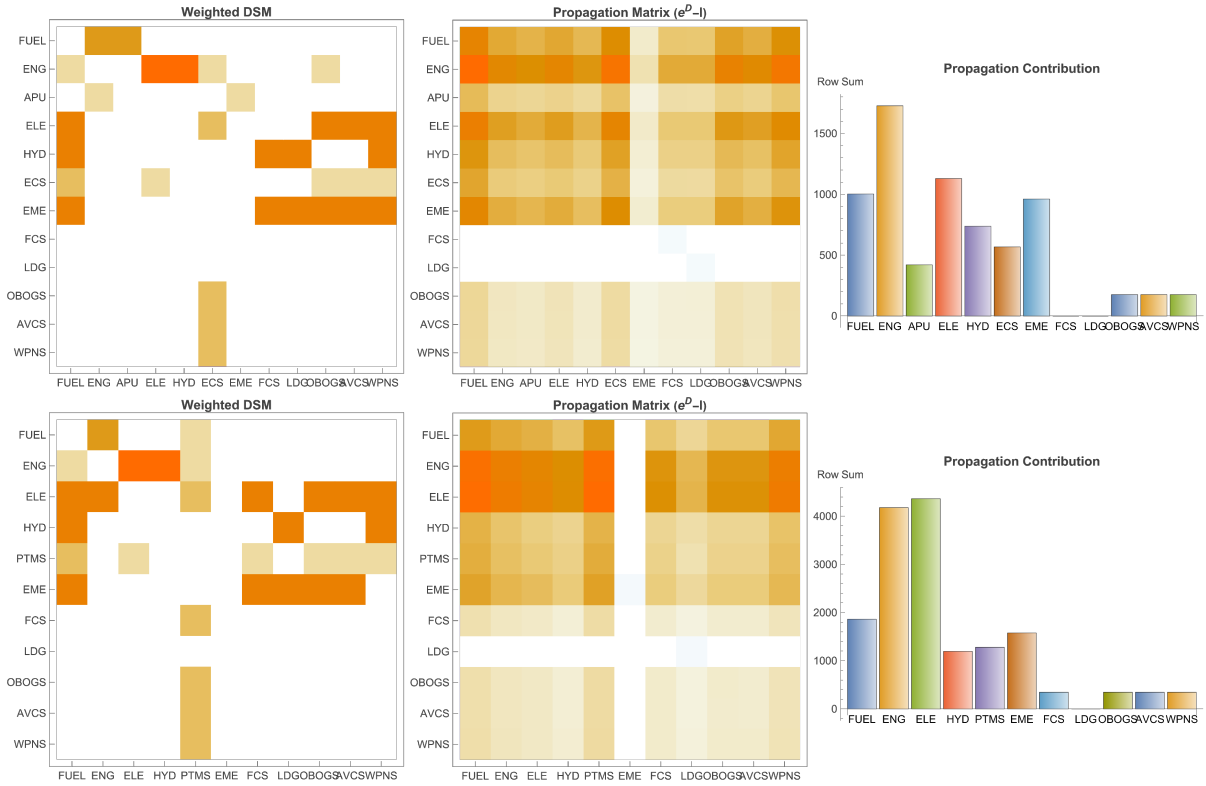


Figure 9 – Weighted Propagation Cost (WPC) matrices and on-board system contribution for the conventional (upper) and more electric (lower) architectures

5. Discussion

The logical modelling of the on-board systems as black boxes provides a useful abstraction for visualising and analysing the interactions between systems appropriate for early aircraft conceptual design. However, defining the power exchanges between systems is not entirely independent of the physical implementation since it requires a certain degree of prior knowledge of the resources consumed, transformed, and supplied by each system.

As shown by multiple elements of the Dependency Structure Matrix (DSM), multiple operating modes (e.g., degraded states or starting conditions) create new power flows, which could drive system sizing and impact the operational capability of the aircraft (such as dependence on external ground power). One of the limitations of the presented method is the subjective nature of architecture model development. Multiple power interactions were not captured in the DSM, and their relevance depends on engineering judgment, modelling purpose, and the particular moment during the design stage.

Regarding the comparison between the two architectures, the more electric architecture contains one fewer on-board system element but a larger number of inter-system couplings. While these couplings may improve system integration and functionality, they also increase the potential for cascading effects and emergent behaviours. Whether these additional interactions ultimately provide a net benefit or penalty must therefore be assessed at the aircraft level.

Since the logical architecture captures these inter-system interactions, it can be directly analysed as a directed graph, providing a computationally inexpensive means of rapidly evaluating architectural complexity. Nonetheless, the variety of metrics presented in Sec. 3.4 illustrates that there is no universally accepted metric for directly quantifying system complexity, which impedes arriving at a single universal conclusion when comparing architectures.

The relationship between couplings and complexity is linked to axiomatic design since a higher degree of interconnections implies lower satisfaction of Suh's Independence Axiom, increasing susceptibility to change propagation and emergent behaviours (Krus [24]). Changes introduced in one on-board system can propagate through multiple indirect paths, motivating the use of the Weighted Propagation Cost (WPC) to quantify the cumulative effect of these interactions. The metric also naturally amplifies the numerical difference between architecture candidates given its exponential nature,

a small increase in coupling may create dozens of new propagation paths. In contrast, these effects are not captured by the other nine complexity metrics conventionally used to evaluate on-board system architectures.
Measuring this attribute is important since, according to Maier and Rechtin, the greater the complexity of a system, the more difficult it becomes to design, build, and operate [25]. However, exactly how architectural complexity translates into higher engineering effort, development cost, schedule, or other system "-ilities" remains unclear. Consequently, no single complexity metric should be regarded as universally representative of architectural complexity.
Nonetheless, the evaluation of multiple complexity metrics can provide architects with a broader basis for comparing candidate architectures. Selection, hierarchization, and interpretation of the metrics' results should ultimately be left to the system architect.

6. Conclusion

Aircraft conceptual design requires methods to evaluate complete on-board system architectures rather than individual systems in isolation. This paper presented a method for modelling coupled aircraft on-board system architectures from a power management perspective to support architecture evaluation during aircraft conceptual design. Representing on-board systems as power-exchanging black boxes enables the identification of inter-system couplings and the assessment of architectural complexity, considering cascading effects. While conventional complexity metrics produced differing assessments, the proposed Weighted Propagation Cost metric captured propagation effects that are not reflected by traditional metrics. The proposed methods provide designers with additional information to compare candidate architectures during the early design stages and prioritize subsequent design efforts.
In conclusion, the objective is not to optimize individual systems or even on-board system architectures, but to achieve a more balanced aircraft that better satisfies its design requirements.

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