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Fixed-Wing Aeroplane (Sub)System Design Method: From Abstract to Material Architectures

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This paper presents development of an innovative method for aeroplane system architecture design, based on the principles of causal networks. In light of the environmental crisis that the world faces, it is argued that the new design method should be motivated by sustainability values in the first place. This implies the necessity for a method that is evolvable, as well as for the design artefact to include an awareness of its contribution to dynamics of the higher-level systems within which it is embedded. To that end, the method is based on gradual and iterative development of an initial abstract object which represents relevant system functions over a designated life cycle. The architecture design procedure consists in evolving this abstract object by means of the pre-defined design rules towards a material architectures that satisfies multiple requirements and constraints for multiple actors. The design rules at hand represent a combination of quantitative methods such as first principles of physics and qualitative principles of systems engineering. In complement to system characteristics, rigorous book-keeping of matter and energy interfaces with the object's surroundings is at the core of the method. To test the developed principles with the elementary method development at hand, a propulsive system architecture case study is elaborated. The case study represents a simple case of a short-medium range engine architecture designed to respond to operating requirements, whose resulting performance is book-kept and evaluated in a much broader context than the operation (in-flight performance), for which engines are commonly preliminary-designed.

I. Introduction

A. Background

The context driving the contemporary and future developments of civil aviation technology is based on efforts by the civil aviation sector to reconcile its growth tendencies with its current - as well as potential future impact on the natural environment. This translates further into perspectives for rapidly changing vehicle-level and subsystem technological paradigms accompanied by explorations of different new energy carriers, new operation practices, brought together in a great multitude of potential combined approaches. (an elaboration of evolution of this complex landscape is presented in a companion paper by the current authors [1])

Arguably the most prominent pathway in search for a desirable environmentally-sustainable future for the aviation sector is the technological improvement. In (recent) history, the fixed-wing civil aeroplane design space has grown to encompass a practically unmanageable number of theoretical concepts, many of which have been explored only scarcely by the community, and many more of which might never end up being explored. [2, 3] The innovative design space whose richness and diversity dwarf practically the entirety of the concept space that was designed and built (i.e. commercially operated) since the dawn of aviation owes its existence to the rising global pressures on the aeronautical industry just as much it does to the ingenuity and creativity of the people who contributed to its creation. The innovative aeroplane designs could have potential to make a step change for the industry by allowing to achieve high system level efficiencies, which translate into lower fuel and/or energy consumption, and by extension an environmental impact compatible with sustainability objectives for the industry.

However, approaching such complex multi-level, multi-actor problem requires putting together the representative variety of appropriate requirements, constraints, needs and desires, relationships and interfaces under a common

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trade-off framework. In the framework of academic aeroplane preliminary design methods, this translates into a need for extension of the scope of conventional methods based primarily on operating performance of the system (e.g. the classic texts on whole-aeroplane preliminary design by Torenbeek [4], Roskam [5] or Raymer [6], and engine preliminary design such as Mattingly [7] or Cumpsty [8]). In attempts to complement those, or to devise methods to analyse a part of the design space of interest to a given party, a wealth of valuable work has been done by the community, commonly resorting to statistical/surrogate model based approaches [9], as well as to more analytical-based modelling nonetheless limited in scope to certain applications such as hybrid-energy aircraft. [10]

While not necessarily relevant from the point of view of the mainstream industry – which has embarked on a pathway to address the questions of sustainable growth either by employment of new and potentially cleaner energy sources/carriers and by continuing search for further optima with the conventional aeroplane system architectures (e.g. the "ZEROe" initiative from Airbus [11]) – academic interest in new methods for systems architecture design and evaluation is maintained. The motivation is all the more reinforced by the fact that the decision-making in the new design space has become more complicated than has been the case historically. While the involved actors such as aeroplane or system designers are "thinking big" in bringing about the change for the industry, the big-picture decision making is ultimately decided on a much broader scale than the local systems in jurisdiction of the individual actors. The "energy transition" and "sustainable" growth scenarios are unmistakably connected to the capability of the natural and the complex surrounding industrial world to materially support that transition. A simple argument in favour of this observation is the supply chain crisis experienced by the sector since 2023. [12]) Looking at the aviation sectors promising growth, electrification, reliance on alternative "sustainable" energy vectors that in turn could increase energy demand, it is instructive to remember that all such promises are made in a world of depletion and rarefaction or raw materials, which exacerbates the energy requirements and could likely result in greater pollution. The presented ongoing work therefore proposes a way to build a bridge between the world of ideas and concepts and the world of realistically attainable possibilities constrained by conservation laws of the material world.

A somewhat abstract way to frame the problem of the conventional approaches ineptitude to properly confront the the contemporary context and the new design space goes back to inherent limitations of empirical methods. The robustness of the results and of the subsequent design and development at low computational cost, that such methods enable, rely strongly on the underlying model data that are classified into relatively few distinct categories, e.g. mission type, airframe configuration, propulsive system architecture. The thesis driving the work presented in this paper is that a preliminary architecture design method largely agnostic to such data and such categories could be devised based on principles of systems engineering in conjunction with quantitative modelling of systems behaviour. As such could, it could contribute to confronting the entangled decision-making spaces, and navigate them flexibly, without getting locked into a single solution that might fare well once the environment changes.

B. Paper Objectives

The overarching objective is to present a further and complementary development of a previously presented framework for abstract-to-material aircraft systems architecture design [13], in further pursuit of comprehensive and coherent trade space representative of the challenges that the contemporary aeroplane and its constituent systems are confronted with. The adage shared by Roskam in his 1985 classic text on preliminary sizing [5] says that the aeroplane preliminary sizing phase would lock in some 90% of the life cycle (financial) cost of the product. With today's big-picture awareness of the natural and social requirements and constraints, the underlining reasoning should likely stay the same, but it ought to be re-contextualised to a more elaborate objective variable describing more than simple financial reality of an aeroplane development program.

To that end, the work presented in this paper aims to employ an abstract formalism based on parametric coarse-graining of a system of interest, and on subsequent representation thereof in form of causal networks. Akin to conventional preliminary sizing of gas-turbine engines, which take simple abstract thermodynamic cycle as the starting point to subsequently materialise it into anything between a basic gas turbine to a very intricate multi-spool turbofan engine architecture, the aim of the proposed system architecture preliminary design method is to:

1) Define a primitive starting point for the system architecture design, characterised by a minimal number of system parameters (granularity) that meaningfully represents the design artefact over a comprehensive life cycle. [1]
2) Define a process to successively increase the system granularity of this primitive system in the direction(s) of interest to the designer, that is in the direction of the whole-system development, or development only of subsystems of interest. The decision making in this iterative development is to be guided by the constant re-evaluation of the figures of merit representative of the complex environment in which the system is meant to

be embedded.

To that end, the paper is organised as follows. Chapter II presents a brief overview of the precedents upon which the current work is founded. Chapter III presents the conceptual and theoretical framework which constitute the basis for the architecture preliminary design method. Chapter IV presents the elaboration of the method in its current form. Chapter V describes an application case of a simple turbofan engine architecture development whose reality is captured over a scope somewhat broader than in-flight operation alone. Chapter VI provides a critical discussion and potential merits of the method on the basis of the presented studies, with Chapter VII providing a conclusion and overview of ongoing and further developments.

II. State of the Art and Related Works

This work draws some inspiration from Paynter's initial elaboration of "bond graph" formalism, which aims to provide a common ground for distinct engineering disciplines to interface and communicate when analysing and/or designing multi-disciplinary engineering systems. [14] On the basis of energy continuity and power balance, Paynter's formalism relies on a unifying principle of power transmission instantiated in different forms depending on the discipline or type of system being represented (e.g. electrical, thermal, hydraulic). This way, an abstract network could be used to represent a system, upon which a materialisation could be imprinted at a later stage to represent a real system. The work presented in this paper does not resort explicitly to bond graph formalism. Some further elaboration on bond graphs, more recent than Paynter's initial formulation, can be found in Borutzky (ed.) [15] for general applications, and in Liscouët-Hanke [16] for particular application in design and optimisation of civil aeroplane power system architectures.

Other papers by the current authors provide crucially important background for the current work. Reference [2] presented an initial formulation of function-to-form mapping framework to describe the aeroplane design space populated by more varied and diverse aeroplane concepts than the conventional "Tube and Wing". Reference [3] expands upon that basis, presenting a more comprehensive design space overview and arguing for existence of a global tendency to seek higher system efficiency and/or performance peaks by mapping more functions onto fewer forms; for instance: attempts at boundary-layer ingestion distributed propulsion aim to employ a single structure to provide both lift and thrust, at lower weight and drag count. On that basis, existence of an asymptotic minimal performance of a theoretical fully-integrated (also referred to as "minimal" or "primitive") aeroplane system architecture is inferred. The work presented in the current paper is predicated upon hypothesis that this theoretical "minimal state" could be correlated to a primitive system architecture description, and subsequently used as a starting point for a blank-sheet (sub)system architecture iterative design process within a multi-scale, multi-actor, multi-objective design space. Furthermore, the necessity for incorporating the rudimentary life-cycle correlations already at the initial primitive state of the system (even when designing only for in-operation performance of a subsystem, e.g. an engine) is derived in the companion paper which describes complex relationship between the aeroplane engine and its broader environment at different scales. [1]

Another related paper [17] presents an in-depth elaboration of the causal network framework, its basic principles, and utility in devising algorithms that search system sizing solutions in unknown spaces, to make them more representative of a comprehensive operating envelope of interest. While the application case for the algorithm was multi-point sizing of an *a priori* known turbofan engine architecture model, the philosophy of modelling a system as a causal network that iteratively grows in scope from a more primitive to a more elaborate state representing a broader operating envelope links it directly with the work presented in the current paper.

Finally, an initial version of the method described in the current paper [13] presents an elementary thermodynamics-based blank-sheet system architecture design algorithm and its application to a civil-aeroplane environmental control system (ECS) case at a single operating point. The method consisted of creation of a system architecture by concatenation of pre-coded elementary processes, with the decision making being guided by evaluation of thermodynamic figures of merit such as invested work, exergy balance or process thermodynamic efficiency. For a given objective, a primitive system would be preliminary-optimised with respect to one such system-level objective variable, and the subsequent architecture design process would be guided by this reference "minimal" state.

III. Theoretical Framework Elaboration

A. Coarse-Grained Systems and Causal Networks

The elementary premise for the work is the fundamental notion of "coarse-graining", which says that any real system of interest could be conceptually represented (modelled) by *coarse-graining* it into an arbitrary finite number of mutually correlated objects. Many equivalent coarse-graining scenarios are possible for any object of interest, depending on the desired level of detail and/or available computational power at the given context. For instance, a compression process could be coarse-grained over space and time by a succession of several constituent compressions, or further into a pressure field resolved over a fine spatio-temporal grid, or further down even to the level of individual particle motions. Equivalently, an *a priori* known object such as a compressor component could be coarse-grained into distinct compressor stages, then further into blades, hub disks, casings, and the individual nuts and bolts of the machine. As such, coarse-graining is evidently a recurring process, that is - each object could in principle be further divided into more objects; analogously, any observed object could itself be a constituent of a higher-level coarse-grained object. Figure 1 provides an illustration of the concept, with the aeroplane example focusing only on a single element of each successive description level, i.e. implicitly alongside with the engine one would find the wing, the airframe, the environmental control system, the avionics...each prone to the coarse-graining process in its own right.

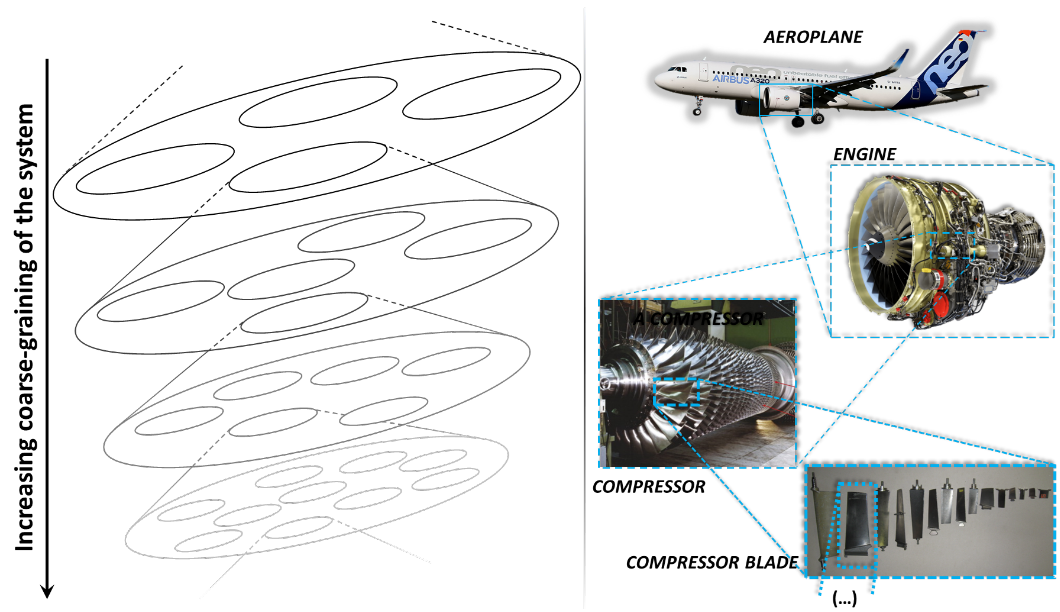

Fig. 1 The abstract concept of coarse-graining (left), illustrated on the example of the aeroplane, its engine, and subsequent increasingly-detailed description levels (right). (adapted from [3])

Furthermore, the objects of the coarse-graining process can be identified with parameters that constitute the mathematical space describing the system of interest. When directions of causal influence that the parameters exert on each other are attributed to the correlations linking them, the system is represented as a causal network. Assuming a unique direction of the flow of causality in nature, the causal flow within the system model is identified with the nature of the constituent parameters. The parameters are categorised in two subsets: *Data* parameters, which can exert causal influence on adjacent parameters, but do not have any causal precedent themselves, and *Model Variable* parameters, which have a causal precedent and can exert causal influence on other parameters as well. (Fig.2) An intuitive example would be a flow through a duct, where the natural state can be described as the duct geometry causes the mass flow through it to be what it is, rather than the other way around. In a causal network model, this would translate into a Data parameter for the duct cross-section area, and a Model Variable parameter for the duct mass flow.

A subtle insight hidden in such formalism is that the Model Variable parameters mirror the reality of the system of interest in isolation, and that the Data parameters mirror the environment of the system, or in particular - represent the boundary of the system. Given that the causal network can extend in directions that represent physical scope of the system, temporal scope of the system, and level of detail of the system, it follows that the system boundary can

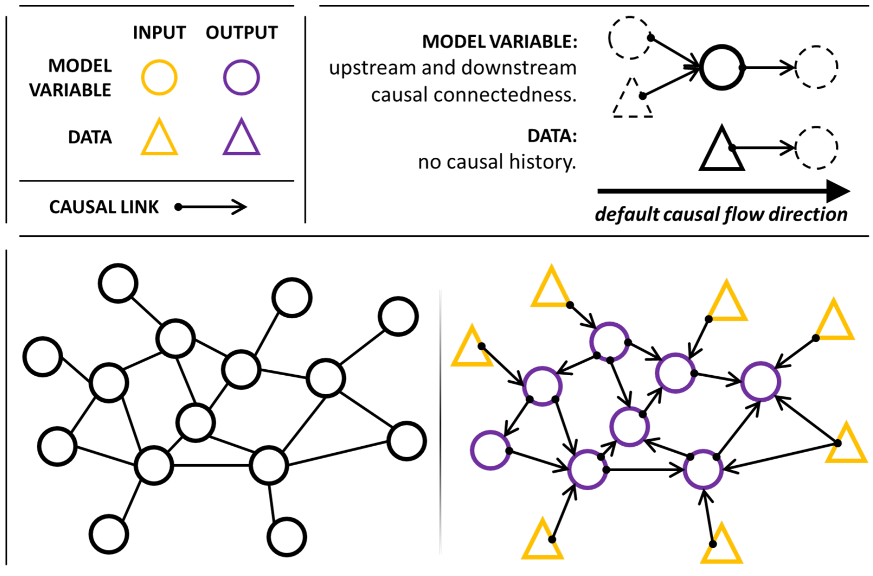

Fig. 2 Parameter categories used for defining causal networks (above). System represented as a basic coarse-grained correlated network of parameters (bottom left) and the same system represented as a causal network (bottom right). (adapted from [17])

be represented as a complex boundary of a system whose description can be more comprehensive, representative of multiple states across a comprehensive life cycle. This approach is in contrast with a more traditional view of a design object which represents a set of features satisfying objective operational physical requirements.

The capacity of a model to manipulate the causality flow of the network stands at the core of any system design process. From this point of view, any system design process can be summarised as iterative design of the system boundary and of the system itself until a full state which faithfully represents both the environment and the system is reached. A typical example of such point of view is any preliminary sizing process which leans upon empirical data tables for its operation. The common procedure with those methods is to firstly impose a targeted system state in order to scale the Data to fit the current design purpose, and then subsequently use the obtained scaled Data in conjunction with system control parameters to explore the behaviour of the system as given by the Model Variables. This iterative interplay between sizing of the system and of the environment in turn can explain in simple terms why it is difficult to assess designs that are radically different from the well-known solutions.

Finally, the framework can address multi-level requirements and constraints, which is at the core of the problem addressed by the current work. The environmental impact of the human activities, or even the aeronautical industry alone, is a problem of consolidation of multiple distinct actors in simultaneous cooperation and competition, whose aggregate behaviour influence a high-level system that is beyond the jurisdiction or simply beyond the scope of any of them individually. On the other hand, the causal-network framework fundamentally does not make any distinction between these hierarchy levels. This feature of the formalism can be leveraged to reformulate design methods to incorporate higher-level "awareness" (e.g. natural environment and social requirements and constraints) into decision making when designing smaller-scale systems (e.g. engines or aeroplanes).

For that reason, the design method (elaborated in more detail in the following chapter) derived from such framework postulates that the primitive system description upon which all the subsequent developments will be based needs to provide an elementary description of the system as an object in time, or what is commonly referred to as the *life cycle* of the system. In order to satisfy the higher-level compatibility criterion, the object is interfaced with its broader environment by parameters describing the aggregate flows of "Matter" and "Energy" "IN" and "OUT" of the system during the observed life span. (Fig.3, left) The default state of the causal network associated to that description (Fig.3, right) is that the parameters flowing in to the system are represented as Data, as the system receiving these does not necessarily have the knowledge of the upstream causality behind those. On the other hand, as the outward flows are direct consequence of what the system does over its life cycle, those are represented as Model Variables by default. Any system behaviour will equally depend on the knowledge about the causally-adjacent systems, which is why the

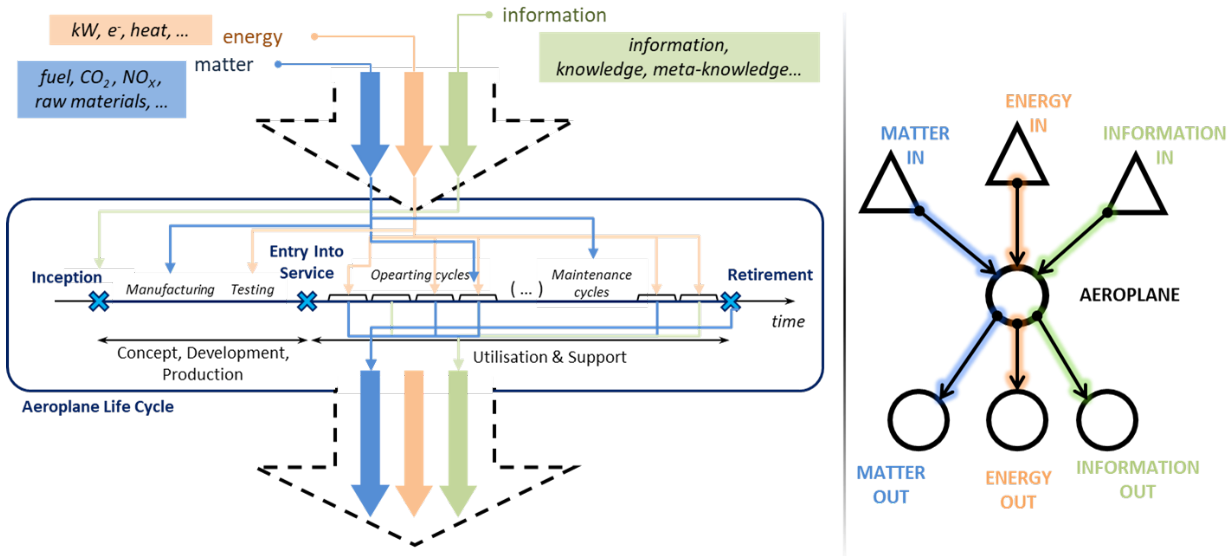

Fig. 3 Schematic overview of aeroplane as a life cycle, and the cumulative Matter/Energy/Information flow interfaces with the higher-level environment and the surrounding systems (right). Analogous representation of the same life cycle in form of a basic causal network. (from [1])

Information flows are defined. In turn, everything that an actor (i.e. the actor governing it) renders transparent in terms of the knowledge of its own system, is represented by the "Information OUT" Model Variable.*

For more details on coarse-graining, causal networks, applications of these principles and their implications for civil aeronautical systems description and design, the interested reader is referred to the related works by the current authors [1, 17].

B. Abstract versus Material System Representation

The previous work [13] introduced definitions of abstract and material systems for the purpose of delineating a theoretical "minimal" performance system from a real material system that operates in real environment and at more realistic levels than those described by the abstract architecture. An example of the idea was drawn from equivalence between a thermodynamic cycle and a real gas-turbine engine which materialises the principles of the cycle. The former would be labeled "abstract" system, as something that captures a behaviour of interest, but is not materially conceivable, whereas the latter would be labeled a "material" system, one of many possible material embodiments of the same underlying abstract object. An "abstract" Joule-Brayton power cycle is the basis for derivation of a multitude of possible gas-turbine engine architectures, between turbojets, turboshafts, turbofans, just as well as their variants with a single spool, two spools, etc. (Fig.4)

In the current work based on more rigorous definitions of causal network framework, such definition of abstract and material system no longer seems meaningful. Firstly, the coarse-graining process puts all parameters that could be used in a model on equal footing. If there exist practically infinitely many ways to describe physical reality of a system using a set of parameters, a choice of which ones to characterise as "abstract" (implying an unreal aspect to their nature) and which ones as "material" (realistic in opposition to their counterpart) turns into an arbitrary exercise highly prone to the subjectivity of the observer analysing the system. This is all the more poignant when intermediary solutions are considered, somewhere along the numerous development pathways between an "abstract" starting point and a "material" destination of the design process. Since that framework postulates that components could be materialised one by one, or even at design phases completely remote from one another, insisting on the abstract-material dichotomy might provoke more confusion than it could provide clarity.

However, there is interest in remaining the notional abstract-material formalism, as the overarching goal remains to use an abstract description agnostic to most of the practical categories of the real world (e.g. see Fig.5 in the following

*It can be argued that all of the presented parameters are just different instances of the "Information" category, but a deeper elaboration would largely exceed the scope of the current paper.

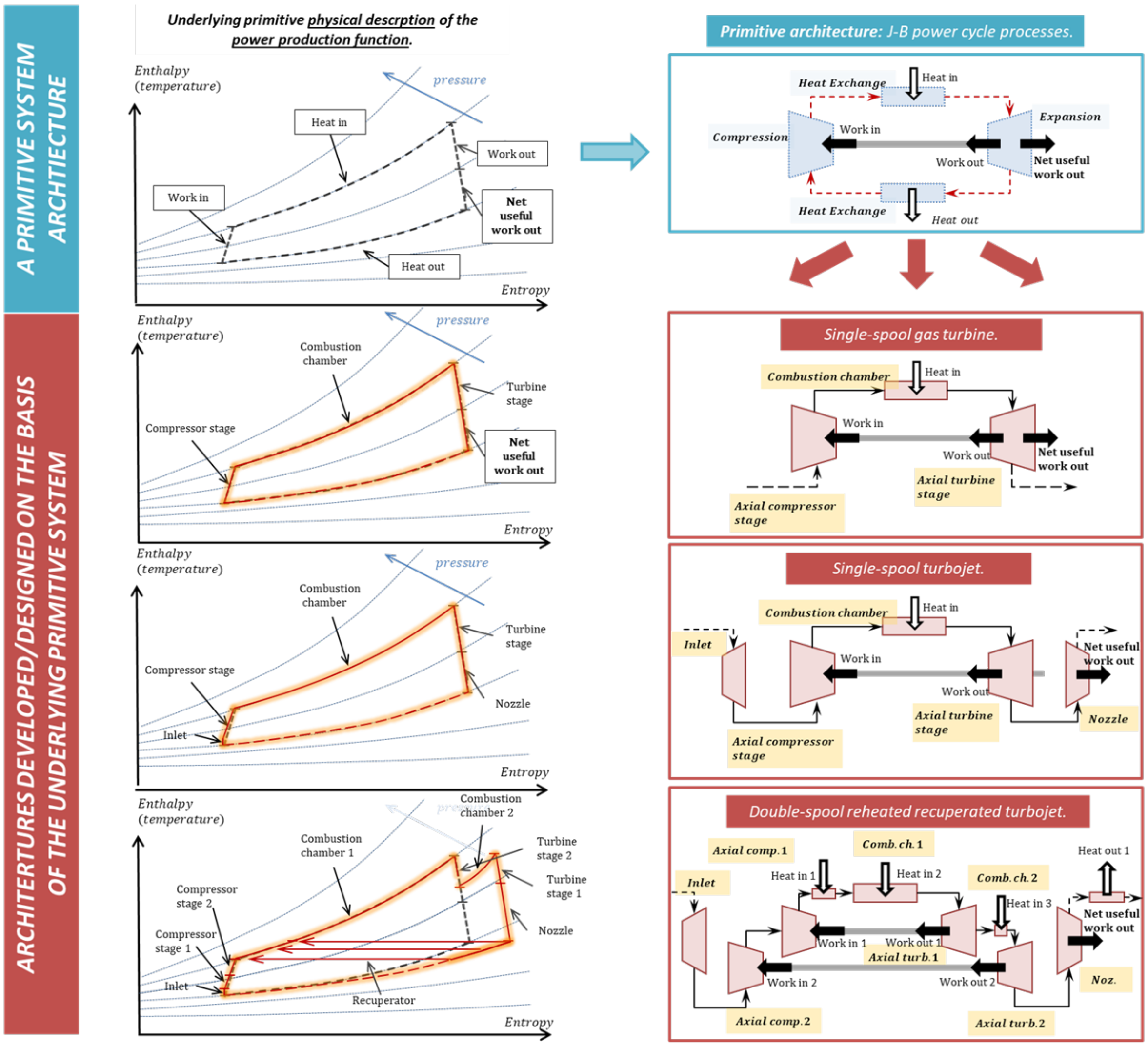

Fig. 4 Development of various gas-turbine engine architectures on the basis of the same underlying primitive architecture that spans thermodynamic parametric space: the classic Joule-Brayton thermodynamic cycle.

chapter for illustration of this statement), to design objects to be ultimately materialised (produced and operated) precisely in the real world. Therefore, the primitive description and the overall framework will still be referred to as "abstract". In turn, this abstract formalism purports to capture the representative "material" reality of the system at all times either by a full parametric determined state of a reality representative of both the system and its relationship with the environment.

IV. System Architecture Design Method

A. Overview

In earlier and concurrent works by the authors [2, 3, 13], employ function to form mapping formalism to infer existence of a general abstraction of an aeroplane, which can be correlated to a "minimal system state". In the preceding work, this asymptotic abstract state was measured in operating energy, akin to earlier elaborations by McMasters [18] and Bejan [19], who in their respective ways postulated existence of theoretical minimum energy for flight of any self-propelled object, be it a spontaneously (naturally) evolved flying animal or artificially designed artefact like an aircraft. This theoretical abstract state could in principle be quantified in any figure of merit represented in the mathematical space that describes the baseline design object. Given that the primitive object is now meant to represent a comprehensive life cycle of a system, there could be many different figures of merit involved, including - but not exclusively limited to - the operating energy.

The basic principle of the proposed method is to initiate the system architecture design with an elementary causal network representing a system over a minimal life cycle. (Fig.3, right) On that groundwork, iterative multiplication of the network elements aims to create a system architecture coherent both with high-level requirements and constraints, as well as with its local specifications. In other words, the architecture design method can be summarised in its entirety as a process of increasing of the system coarse-graining from the primitive network to a final state satisfactory to the designer. The increase in coarse-graining is done in three distinct ways, all equivalent from the abstract point of view of the causal-network formalism point of view, but distinguished in practice for their real-world significance:

1) In the "direction" of increasing system scope: adding extra details to the system outside of its current boundary (Fig.5, top), and/or
2) In the "direction" of increased level of detail: adding extra details to the system within its current boundary (Fig.5, center), and/or
3) In the "direction" of longer time span: adding extra successive states to the system, to broaden the system life cycle. (Fig.5, bottom)

That way, a blank-sheet architecture design can be carried out without being constrained early on by heuristics or data which could be misleading or outright obsolete when exploring unknown architecture sizing spaces. Such method

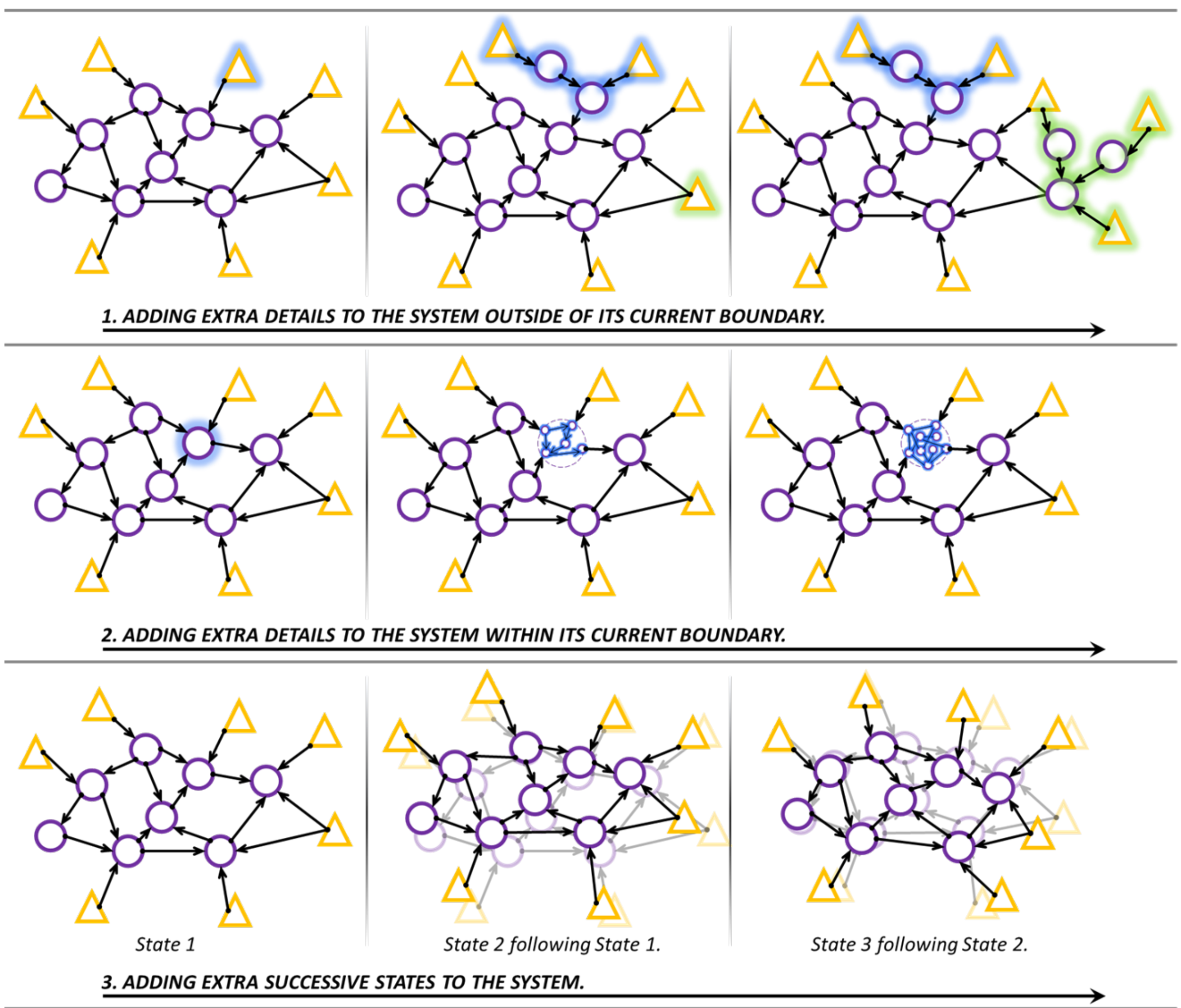

Fig. 5 Three distinct and complementary ways to grow a causal network that represents a system.

would arguably allow the designer to pursue fully transparent full-system sizing with a complete grasp of:

- The system boundary with the meaningfully represented complex environment,
- The full-system division into constituent subsystems,
- Pursuit of various "function-to-form mapping" design scenarios.

Almost by definition, system architecture design revolves around seeking some sort of "optimal" solution under constraints imposed by limited resources: energy, matter, human-power, time, or knowledge. Conventionally, big-scale system design would be articulated by putting pieces together and observing the spontaneously emerging behaviour, which cannot result in an optimum big-scale result. By posing the design problem as a path between big-picture-aware abstraction and fully transparently developed designs, arguably better multi-level optima in arbitrary desirable part of the design space could be reached, where the system performance is in coherence with limits imposed by the dynamics of the complex system environment.

To that end, the method is conceptually split into two tightly linked inter-operable segments described in the following sections.

B. The Overarching Rules

The fundamental principle of the whole method is that of **causal closure**, which requires that every element of the system have its state causally determined, i.e. that the full information on the system must be provided at every step of the system design. Such condition is in any case mandated from the mathematical point of view, for the system to be coherent and well-determined. The causal closure principle made explicit here is meant to reflect the awareness of the higher-level system - in the current context the natural environment - which relies on the global dynamics of matter and energy. Therefore, the closure is an extra step for the designer to take to make sure that the energy and matter provisions for the designed systems are being minimised. In turn, where the matter/energy flow loops would not be closed, which is bound to happen somewhere due to the conservation laws - the resulting information is mediated to the environment about the "Matter" and "Energy" flows "IN" and "OUT" of the system. That way, design outcome can be more meaningfully evaluated in light of the broader environment requirements and constraints, and subsequently integrated into it. For instance, if the system includes an energy-consuming component, the designer will have two choices to proceed further:

- Do not modify the system architecture, which would add an extra Energy parameter to the network, indicating that energy is drawn from the environment to power the given system component;
- Add extra upstream elements - e.g. elements of a power train, or a local energy source - to close the energy continuity. If the added energy source is an external source (e.g. a battery for an electrical heater rather than redirected hot air that would have been rejected from the system elsewhere), this local source will also require an information element to be added to the network, stating that at that given operating phase the system requires external energy input.

The overarching framework also includes the catalogue of basic components that can be used in system architecture design by being added to the primitive network, in turn changing the overall system state aiming to move it towards a state desirable for the engineer and compatible with the high-level constraints. In the presented preliminary developments, the components are still being serially concatenated between starting operating conditions and the final objective state. The components represent thermodynamic components with additional simple correlations to capture their features relevant for life cycle phases other than physical operation. An example of a component used in the current development is given in Fig.6 The network represents the default state of a typical compressor thermodynamic model, where on the basis of input state and the correlations, the final output state can be calculated. The model is fully causally closed, yet it is not determined until all the "Information IN" parameters have been determined. From the point of view of the model, this represents the information arriving from the environment, in this particular case - upstream of the compressor. Practically speaking for the designer, these parameters are the input to be provided to be able to calculate the final model state. Note the book-keeping included in the model, represented by the "Matter/Energy IN/OUT" labels next to all instances of mass-flow and energy parameters.

Finally, while the above compressor example represents physical in-operation reality alone, the method includes a rudimentary description of comprehensive life cycle phases of the component/system. This representation is made by means of simple labelling of the causal network parameters, to indicate which phase they represent and include them correctly in the life-cycle book-keeping. For the compressor example described above, the representation is given in Fig.7. The example shows a compressor as a causal network in the default causal state, spanning multiple points of the life cycle: Design and development, Manufacturing, Operation (Takeoff point given as an example),

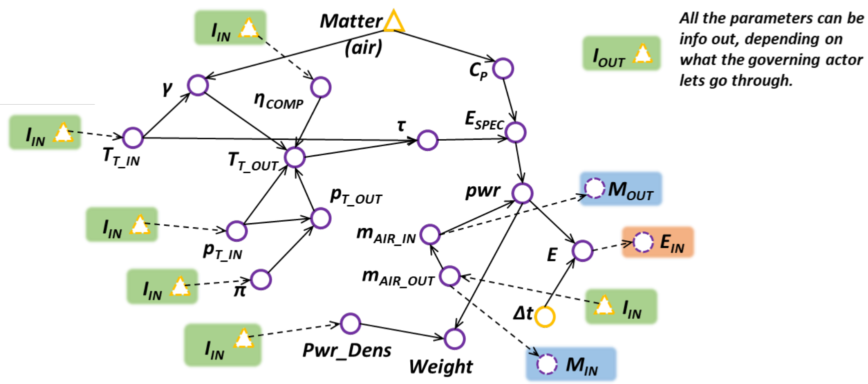

Fig. 6 Elementary example component: compressor thermodynamic model in the default causal state.

and Maintenance. For example, what was previously unknown information on compressor efficiency η_{comp} is now an outcome of two user-defined Data parameters "Technical experience" and Δt, indicative of the expertise of the design team whose result is in turn correlated with the time they are allocated to develop the given feature of the component. Note fore example the parameters "Maintenance frequency" and $N_{Op.Cycles}$, which are causally connected to "Information IN" parameters. These can be thought of representing input from hypothetical regulation authorities and customers demanding compressor (i.e. by extension aeroplane) operational frequency. The principle of Matter, Energy and Information bookkeeping remains the same as before.

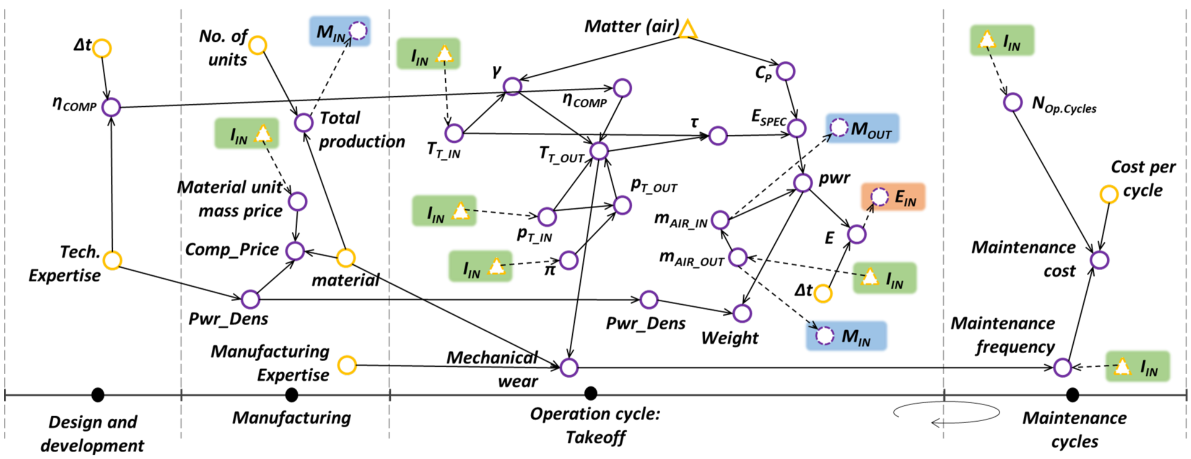

Fig. 7 Elementary example component: compressor over a rudimentary life cycle.

No consideration of different actors involved in the system life cycle is made, i.e. the entire life cycle is visible by a single stakeholder in charge of its design, operation, maintenance, etc. For that reason, parameters such as "Number of (produced) units" or "Cost per (maintenance)" are categorised as control Model Variables rather than as Data, as from this global point of view they do not represent knowledge of an outside actor. A more realistic picture, object of the ongoing developments, would include actors whose visibility of the system might map onto different system life phases, e.g. an airliner can be considered to see the system only throughout the operation phase, whereas an airframe manufacturer would mainly see that subsystem in its pre-operation phases.

C. The Architecture Design Process

With the basic rules and structures presented in the previous section in hand, the architecture design process consists of iteratively growing a representative primitive network in a coherent and consistent manner until a state is reached that faithfully represents the reality of the system dedicated to a given purpose (function). The flow chart representation of the architecture design process is presented in Fig.8.

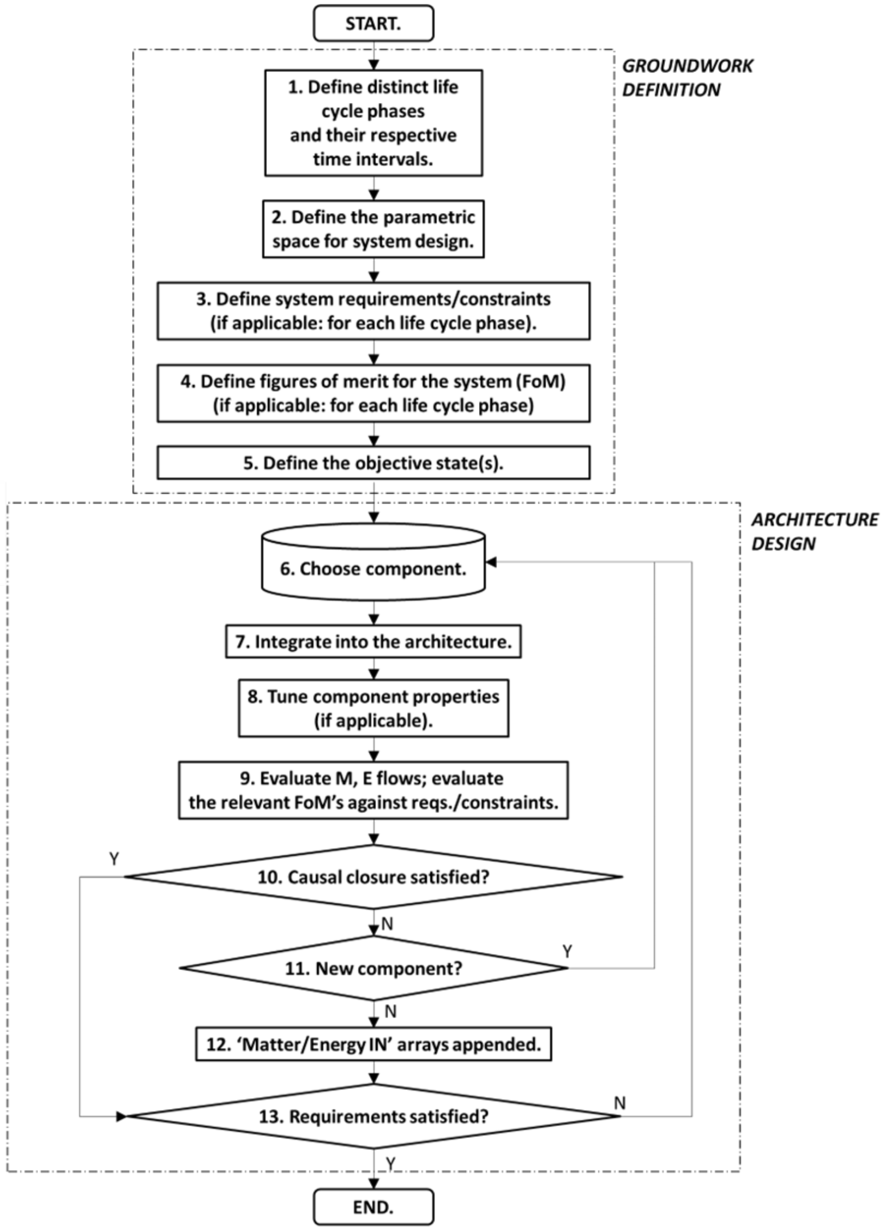

Fig. 8 Flow chart of the architecture design process.

The process is split in two main parts. The first part concerns setting setting up the primitive causal network, whereas the second part deals with the architecture design. The first part starts with definition of the system life cycle by declaration of the life cycle phases of interest, along with their respective time intervals. The life-cycle intervals add up to the total life cycle period of the system. (step 1) Then, the parametric space for system modelling is to be defined, which represents an initial system coarse-graining. (step 2) NB: given the high-level system boundary being represented by flows of matter and energy in and out of the system, the parametric space to be defined must be compatible with these. With the parametric space defined, requirements and constraints on the system can be provided (step 3); if applicable, these can be given for all the life cycle phases defined in step 1. In order to be able to guide the decision making during the system architecture design, the relevant figures of merit ought to be defined next (step 4), either for the life cycle as a whole (e.g. aggregate cost over the life cycle) or for distinct phases of interest alone. Finally, the objective states for the system should be defined at the life cycle phases of interest. (step 5)

At the moment of production of this paper, the complete rudimentary life-cycle network is still being constructed, with only the basic Matter/Energy/Information high-level network being available. The design steps are based on successive additions of system components within this high-level boundary to constitute a network. Nonetheless, this does bears no impact on the main message of the presented work.

With the groundwork constructed in the first part, the second part of the process can begin. The user can now choose a component from the component catalogue (step 6) to be added to the baseline. (step 7) Addition of the component will incur changes in the life-cycle parameters it is correlated with, as well as in the high-level parameters at the system boundary. The component properties can be tuned by the user if so desired/necessary. (step 8) The impact of the newly added and tuned component is then evaluated against the system requirements and constraints. (step 9) Causal closure based on Matter and Energy loop closure is then evaluated. (step 10) If causal closure is not satisfied - which is always the case, since the condition is predicated upon matter and energy conservation - the user is asked whether they want the closure to be made with additional components that provide the required Matter or Energy (step 11). If so, they are returned to step 5; if they prefer to move on with the initial architecture design, the values of the matter or energy parameters necessary for the causal closure are stored the "Matter IN/OUT" or "Energy IN/OUT" arrays, to be included in the final result. The process is repeated until the design requirements and constraints are satisfied. (step 13)

The final result at the end of this architecture design process consists of:

1) System architecture described as a causal network spanning a life cycle;
2) The state of this causal network;
3) The state of the parameters at the system boundary with the high-level environment, including:
    a Aggregate amount of the Matter species required by the system ("Matter IN" parameters);
    b Aggregate amount of the Matter species produced and rejected by the system ("Matter OUT" parameters);
    c Aggregate amount of various types of Energy required by the system ("Energy IN" parameters);
    d Aggregate amount of various types of Energy produced/rejected by the system ("Energy OUT" parameters);
    e Information about the complex environment transparent to the system ("Information IN");
    f Information about the system rendered transparent to the environment ("Information OUT").

V. Case Study

An elementary test case is elaborated in the following. The goal of the presented study is to demonstrate the developed capabilities of the design process rather than to gain any quantitative insights into the behaviour of the designed system.

A. Case Description and the Test Matrix

In continuation of the earlier development [13] where an environmental control system (ECS) system architecture design space was explored using a rudimentary version of the current approach, the case study of this paper focuses on propulsive system architecture design. The study is very simplified, intending to represent the basic ontology of the design object in a comprehensive manner. The goal at hand is to demonstrate a capability to capture:

- Required in-operation physical performance,
- Resulting features at the other life cycle phases,
- Interactions with adjacent systems,
- For different energy sources,
- With coherent book-keeping of the relevant interfaces through matter and energy flow book-keeping.

For this reason, the basic parametric space used in the study is developed around the classic $0D$ thermodynamic parameters (temperatures, pressures, efficiencies, work, etc.), extended with correlations representing mainly different

OBJECTIVE ARCHITECTURE	LIFE CYCLE PHASES	ADJACENT SYSTEMS	ENERGY CARRIER	SCENARIO
Short-Medium Range Turbofan.	*Design,* *Manufacturing,* *Operation,* *Maintenance.*	***Aeroplane:*** *Airframe.* ***Broader:*** *Energy production.*	*Jet-A fuel.*	*Unconstrained.*

Fig. 9 Test matrix for the case study.

life-cycle cost constituents and engine component properties, which are sufficient to touch upon the adjacent system life-cycle phases.

Figure 9 summarises the cases explored around the baseline scenario of a short-medium turbofan engine architecture design target whose thermodynamic cycle details are representative of a $CFM56$ model. The life-cycle phases represented in the model, with their respective parameters, are:

- **Design:** represented by component efficiencies correlated with parameters characterising the design expertise, cost, time invested into the design, and the resulting price related to the component;
- **Manufacturing:** represented by manufacturing cost for the compressors, correlated with their power densities and the price of the material chosen for the component;
- **Operation:** represented by thermodynamic and cost parameters at two operating points:
  - Takeoff (MTO):
  - Cruise (MCR);
- **Maintenance:** represented by maintenance cost correlated to the number of operating cycles.

For the moment, for technical reasons, only one Data parameter was employed to constrain the engine architecture design. It represents the airframe as an adjacent aeroplane system, by means of the maximum allowable diameter for the engine correlated to the fictitious ground clearance at the engine mounting position on the wing. The parameter is communicated through the "Information IN" array.

The causal flow of the study in this study run is the default unconstrained scenario, where top-level requirements are imposed, and the remainder of the causal network is determined in accordance with the other provided information through "Information IN" array or the user input. The top-level requirements for this system are that of total engine thrust at the two operating points (Fig.10); no requirements were put on other life cycle phases.

	Net Thrust [N]	Thrust_Pri [N]	Thrust_Sec [N]	Altitude [m]	Mach Number [-]	ΔT_{ISA} [K]
MTO	131800	31300	100500	0	0,25	15
MCR	17450	4700	12750	10668	0,8	0

Fig. 10 Design requirements for the engine architecture.

B. Results

The presented design method still consists in part of manual manipulation of the complete network, which is generated by a code that concatenates the pre-defined components. Therefore, the process consisted of adding the components sequentially in pursuit of the final objective of net thrust at given operating conditions. Since the network (i.e. the necessary feedback loops between turbofan engine components) is not yet fully created, in order to ensure the consistency of the obtained results, the thermodynamic parameter outputs were kept in tune with reference results obtained in the gas-turbine engine sizing software PROOSIS^{TM}. [20] As the previous work on this architecture design method [13] focused on exploration of different possible or impossible thermodynamic architectures, in the current development the focus was put on looking at the life-cycle-oriented correlations and impacts. The results are therefore presented as a sequence of figures of merit corresponding to addition of each succeeding component until the required net thrust value is satisfied; this goes for the core part of the engine cycle as well as for the bypass (fan) one. The component addition sequence was as follows:

- **Core:** Compressor, combustion chamber, turbine (driving the compressor), turbine (driving the fan), nozzle;
- **Bypass:** Fan, nozzle.

The unconstrained case is defined from the point of view of the actor designing the life-cycle system without any constraints being imposed either from any of the adjacent systems, local or high-level. Firstly, constituent life cycle times are provided, with intervals chosen arbitrarily:

1) **Component Design:** 10 months,
2) **Component Manufacturing:** 3 weeks,
3) **System Operation - MTO:** 6 minutes,
4) **System Operation - MCR:** 1 hour,
5) **System Maintenance:** 2 days per maintenance cycle.

The "Component" and "System" distinction is made for representing that e.g. Design Phase characteristics are described at a finer granularity with each component-based property being represented, as opposed to e.g. Maintenance

Phase which is sensitive to the whole-system parameters only.

Once the components were added to the initial state, making sure that the system-level requirement and the accompanying geometry constraint were respected, the complete system state was calculated. In the first place, Fig.11 presents the resulting engine architecture state at the two operating points of interest, in the thermodynamic parametric space. In addition to the system requirement, mass flow continuity was assured through the two air streams. Sample thermodynamic details of the cycles are given in Fig.12.

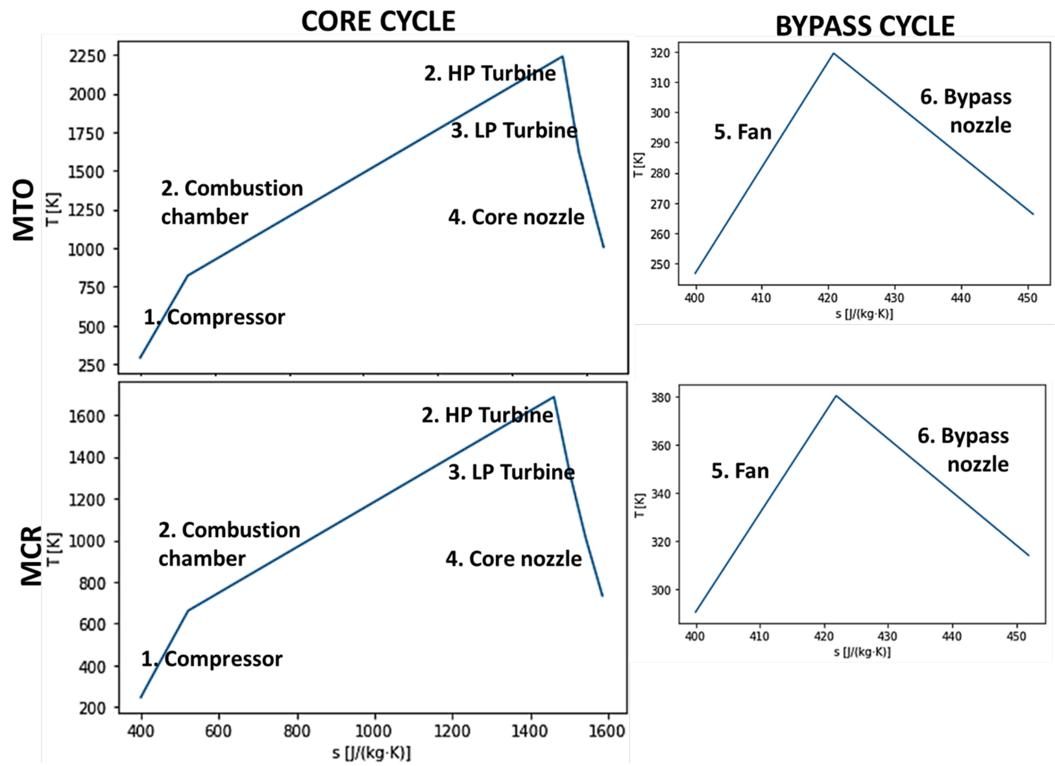

Fig. 11 The designed turbofan engine architectures, represented in the thermodynamic parametric space at the two respective operating points (takeoff/MTO and cruise/MCR), for each individual stream of the engine: core and bypass.

	PTin [Pa]		TTin [K]		PR [-]		ETA [-]		Thrust [N]		Total Thrust [N]	
COMPONENT	MTO	MCR	MTO	MCR	MTO	MCR	MTO	MCR	MTO	MCR	MTO	MCR
AMBIENT	104190,6	36316,09	290,4552	246,8154	1	1	1	1	-	-	-	-
COMPRESSOR	250057,4	83890,16	380,4733	319,4754	10,55	9,3	0,869396689	0,873	-	-	-	-
COMBUSTOR	2638106	780178,5	820,9743	661,7057	1	1	0,999	0,999	-	-	-	-
HP TURBINE	2638106	780178,5	2240,188	1686,693	0,275482	0,362319	0,903175778	0,895	-	-	-	-
LP TURBINE	726750,9	282673,4	1618,953	1315,094	0,294118	0,348432	0,892415972	0,885	-	-	-	
NOZZLE_CORE	213750,3	98492,46	1193,803	1012,381	0,510986	0,280112	1	1	31319	4684,8	31319	4684,8
FAN	104190,6	36316,09	290,4552	246,8154	2,4	2,31	0,917696357	0,9198	-	-		-
NOZZLE_BYPASS	250057,4	83890,16	380,4733	319,4754	0,5848	0,431	1	1	100522	12773,17	131841	17457,97

Fig. 12 Thermodynamic cycle details associated to the cycles from Fig.11.

Furthermore, to illustrate the full scope of the insight the developed method provides to the designer, a sample illustration of the life-cycle oriented parametric space that was determined by the developed engine architecture is provided in Fig.13. The illustration represents the life-cycle representative correlations that the designer of this rudimentary system can manipulate (as long the overarching causal closure condition is respected). More importantly, it provides a state of knowledge far more complete than what one would have with a simple thermodynamic description of an engine. Even in (perfectly realistic) cases where quantitative knowledge might not be readily available, the available insight would make search for the knowledge and communication with exterior parties arguably much more transparent

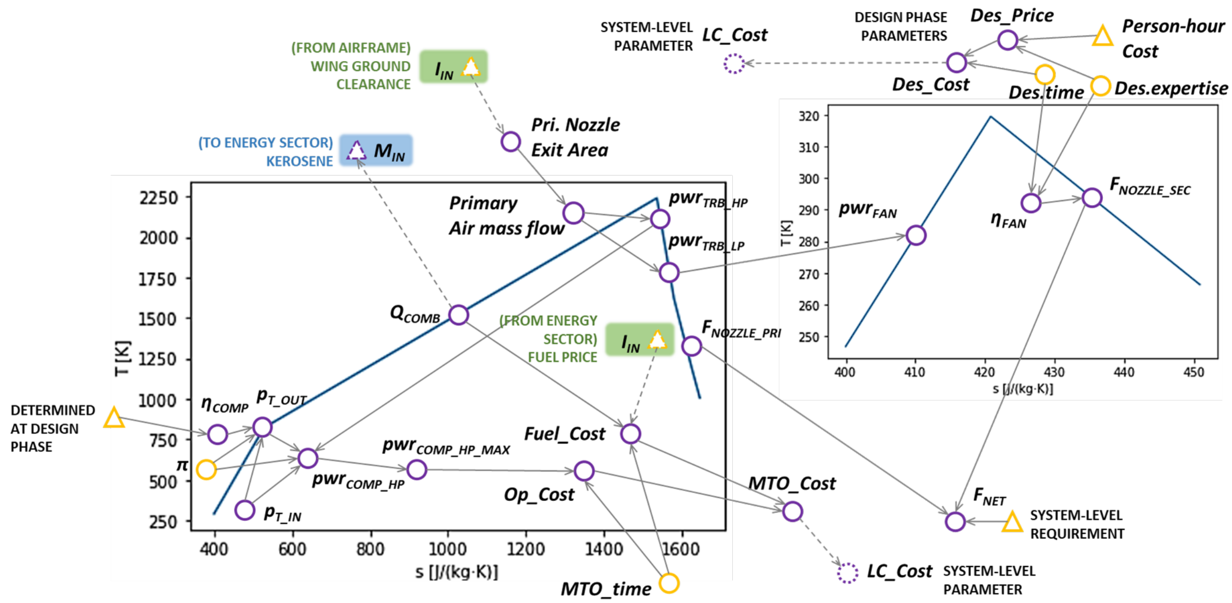

Fig. 13 The designed engine architecture state at Takeoff ('MTO') operating point causally connected to other aspects of the system's life cycle.

and efficient. The presented system depiction at takeoff presents several different types of parameters working in unison. The model variables (circles) mainly represent various aspects of the engine thermodynamic correlations. "Information IN" parameters include wing ground clearance which determines the value of the engine nozzle cross-section areas (taken as representative of the whole-engine diameter) and the fuel price which with the energy for combustion and the time spent at takeoff determines the fuel cost for the phase. Together with the "operating cost" Model Variable here correlated with the compressor power, they yield the aggregate cost necessary to operate the system at these properties during the takeoff, which itself in turn contributes to the life cycle Model Variable "Life Cycle cost" visible outside of the scope of the design system.

Similar consideration was made for instance around a potential inclusion of Manufacturing Phase cost, which was correlated to the fan efficiency parameter. (upper right part of the figure) The fan efficiency Model Variable is seen as an outcome of a pair of parameters "Design Expertise" and "Design time", both represented as control Model Variables at this point. These in turn, along with a prescribed (Data) person-hour cost parameter can determine the component design price, and in turn its own cost, as yet another contributor to the Life Cycle cost system Model Variable. Analogously to the fan efficiency parameter, the compressor efficiency is represented as a Model Variable whose causal precedent is in the design phase of the life cycle.

Note that the injected kerosene is book-kept as a "Matter IN" Data variable whose state is set to output due to the unconstrained nature of the design. Moreover, no Energy IN is necessary to represent at this level, as all the energy driving the system is contained in the book-kept kerosene. A hybrid-electric system would include this parameter as well, for instance.

The thrust requirement for the engine was provided also for the cruise phase. While the designed architecture is the same as at takeoff, the cycle details come out as different due to different operating conditions and the way the individual component behaviour as a function of those. The result, with the associated causal network sample is presented in Fig.14. In this particular case, not too different from the previously discussed takeoff case, simple correlations were included to determine the compressor pressure ratio and efficiency parameters (lower left), by virtue of correlations that emulate the conventional compressor "performance map" which provide a correlation of compressor state variables at various operating conditions. For this reason, the pressure ratio parameter assumed the output Model Variable state where at the takeoff it was a control Model Variable.

Additionally, the turbine efficiency parameter is represented as an outcome of design expertise and the time invested in that life cycle phase, which also results in its cost component to add to the overall Life Cycle cost.

The maintenance-related properties of the systems were determined through correlations between the number of

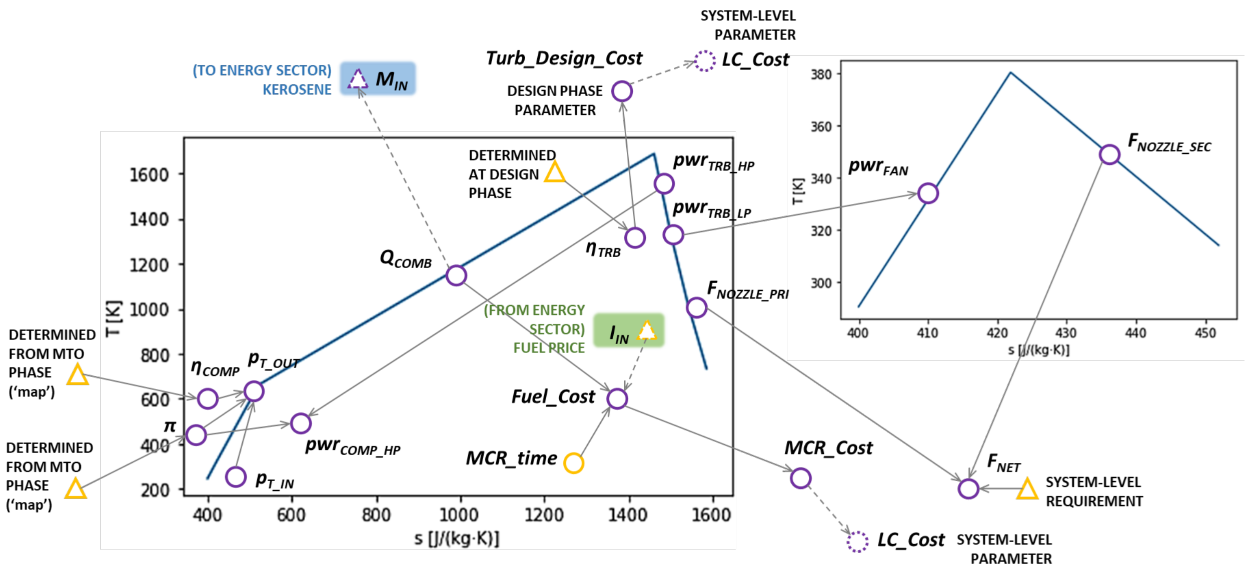

Fig. 14 The designed engine architecture state at Cruise ('MCR') operating point causally connected to other aspects of the system's life cycle.

operating cycles and a maintenance price figure (both assumed to be a free Model Variable in this case), in conjunction with a parameter representing mean time between two maintenance cycles, measured in number of operating cycles. This parameter is causally determined upstream from the Information IN parameter connecting to the airworthiness authorities, who would prescribe safety and reliability norms to be respected by an operator.

Alongside the other mentioned cost parameters determined across the life cycle, the Maintenance cost provides the final input for this system-level output Model Variable. The causal network depicting the coarse-graining of this property of the system's life cycle is presented in Fig.15.

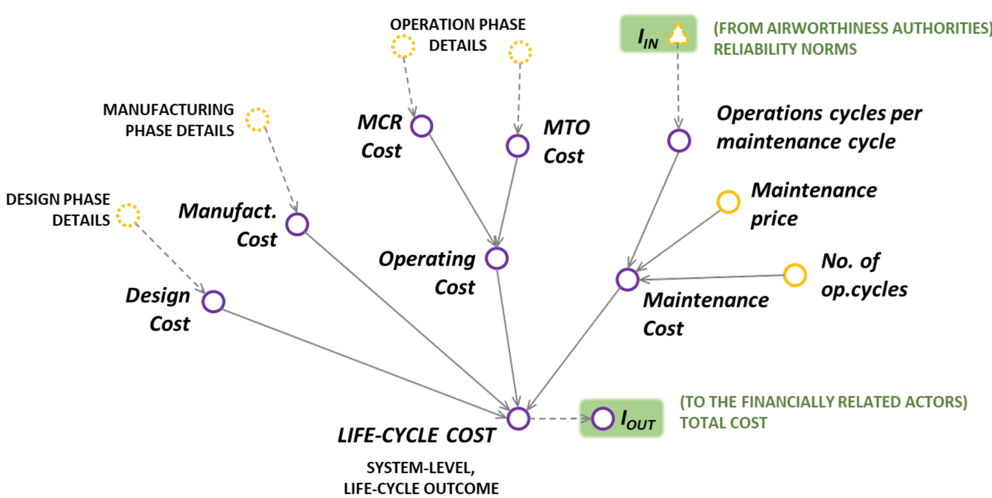

Fig. 15 Causal network representing the system-level property of life-cycle cost of the designed system, related to the local cost parameters determined in Figs.13&14.

VI. Discussion

A. Observations on the System Architecture Design

The novelty of the presented method is in the way it creates system model that represents comprehensive contemporary reality in which complex optima are sought by multiple actors acting at different scales from the very earliest stage of the system architecture design. The approach does not add anything fundamentally different in the domain of the well-established methods of in multi-parametric, multi-constraint optimisation processes. The added value is rather in weaving together the elements that can enable the transparency that is arguably necessary in design of contemporary industrial systems such as civil aeroplanes and its subsystems. The complexity of the contemporary industrial system design problem is characterised the following:

- Multitude of possible concepts inhabiting complex solution spaces,
- The system aims to satisfy multiple actors whose respective points of view on (and expectations from) it will might conflict, leading to sub-optimal or outright wrong solutions,
- The system aims to not be harmful to the natural environment.

Concerning the second point in particular, as presented in the current development the point of view is one of a hypothetical designer with full visibility of the entirety of the life cycle of the developed system. The case of engine architecture development was undertaken for the sake of simplicity, but the same would be true if any other system were approached. To this hypothetically omni-present designer, everything is transparent and immediately accessible to modifications should unanticipated constraints arise from the external environment. This is by far not the case in real life, so in the follow-up, the method will be used to explore the feasibility of reaching system-level results in cases where the system is split up among actors who are not necessarily transparent.

B. Towards a Whole Aeroplane

Moving the model towards a whole-aeroplane representation will come with its own unique challenges which distinguish it from design of engines or environmental control systems (tackled in the previous work). As opposed to those system, determination of the integrated performance of the whole vehicle necessitates a full-profile mass-performance loop. Nevertheless, from the point of view of the presented causal-network framework that will enable that development, all the necessary elements are in place.

To advance towards whole-aeroplane architecture models, the following upgrades to the framework are envisioned:

- Expansion of the existing design process to include basic coarse-grained parametric description of the indispensable aeroplane-level properties at basic granularity levels (e.g. representative of that used in Roskam's preliminary sizing method [5]): lift force, weight, useful volume, geometrical details, as well as the parameters describing the entirety of the operating profile, and the life cycle phases excluded from the current development, such as full mission profile, certification, disposal, etc.
- Define the preliminary system-level figures of merit to reflect:
  - The operating performance of this aeroplane object: specific range, cost-specific range, specific consumption, etc.
  - Life-cycle performance in terms of detailed system cost, full environmental ("Matter" and "Energy" "IN" and "OUT") behaviour, etc.
- Employ the process to increase the system granularity, effectively moving through a vast sizing and design space, and develop various study scenarios for:
  - Breaking the architecture into underlying subsystems,
  - Exploring the influence of the to formulate boundaries between subsystems such that actors can be introduced to the life cycle.

Once accomplished, it means that the trade-offs in architecture design could incorporate model-based rather than conventional data- or "trade factor"-based evaluations of the decision making process in aeroplane architecture preliminary design, compatible with economical, environmental and any other objective variables of interest to the contemporary designer. Moreover, in conjunction with the previously developed capabilities of seeking "minimal states" of a system measured in the figures of merit of interest could enable a full combined bottom-up/top-down architecture design method for iterative search of solutions either in known or unknown parts of the design space. If condensed to the most basic principles, the problem of preliminary design in that design space, facing conflicting high-level requirements and constraints would arguably reduce to:

1) Problem of defining the constituent system boundaries, which reflect the permeability of information indispensable

for making informed trade-offs in the complex environment, and

2) Limits prescribed by the natural laws and material resources which are, to the best of the current knowledge: non-negotiable.

Finally, while the presented study itself is extremely light computationally, made for the purpose of demonstration of basic principles of the developed design process, it is important to emphasise that the design process is meant to be performed at acceptable computational cost for preliminary design. A prospect of providing excessively detailed system descriptions at the preliminary design level can be envisioned, but would would be unacceptable computationally. In contrast - rather than attempting to internalise everything within its own model, the core idea is to internalise only bigger-scale environment representations at sufficiently coarse levels of granularity in order to guide the system design, all while enabling better communication with other subsystems in the collective search of higher-level optima.

VII. Conclusion

A preliminary architecture design and sizing method was elaborated on the basis of causal network formalism. The goal of the presented process is to provide a full *blank-sheet* system architecture design capability with an internalised awareness of higher-level systems and objectives that are beyond the boundaries of the design artefact in isolation. A test case representing a reduced system life-cycle was elaborated to represent short-medium turbofan engine architecture based on an existing thermodynamic model. The system state was calculated for a single design variable, that of an operating thrust; it was constrained by simple correlations influencing its individual parameters such as component efficiencies or nozzle geometries. The resulting life-cycle performance was described with parameters representing Design, Manufacturing, and Maintenance phases of the life cycle, all correlated with some aspects of the physical performance of the architecture at two defined operating points.

This development contributes to devising a more meaningful preliminary architecture design in light of current social and natural circumstances setting potentially requirements and constraints on different constituent systems of the aviation sector. Furthermore, development of different system architectures on the same groundwork can contribute to meaningful comparison of most varied technological (and likely broader than that) solutions across the not-yet-tackled areas of the design space. This can be done in terms of the "local" operational/technological figures of merit of the individual systems, just as well as using higher-level objectives such as fleet economics or environmental impacts.

Ongoing work is dedicated to developing of a comprehensive, representative, full life-cycle representation, as well as to further improvement of the underlying code structure to enable more versatile inclusion of parallel subsystems than it is currently the case. Finally, inclusion of multiple actors involved in the system life cycle is envisioned, with different distributions of system governance and access to information across different life-cycle phases.

Acknowledgments

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