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Analysing the Role of the Propulsive System in the Global Civil Aviation Energy Optimisation Framework

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This paper presents a simple explanatory framework to analyse the diverse strategies proposed by the civil aviation sector in attempts to reconcile its growth tendencies with its impact on natural environment. Despite framing the industry as a single entity that has a problem to solve, it is better represented as a diverse set of actors, each responsible for various constituent systems at different phases of their respective life cycles. To elucidate this multi-actor pursuit of higher-level emergent objectives, the paper firstly presents an overview of different development scenarios dedicated to guide the industry towards sustainability. Given that the constituent systems tackled in such strategies strongly depend on each other, the sustainability objective relies on reconciling all the different agendas and contributions in unison, making them collectively compatible with the dynamics of the socio-economic and the natural world. To analyse the problem coherently, a basic description of an arbitrary system as a coarse-grained closed causal network is formulated. A categorisation for the model parameters is proposed to help define the system boundary and interaction with the environment unambiguously, dispensing with the need to know details of the model that represents the system at hand. This formalism was previously derived for preliminary sizing and performance estimation of aeroplane engines; by virtue of recursive nature of the coarse-graining process, the same formalism can be used to describe systems at any arbitrary levels, which enables a small system (in the current paper the system of interest being the propulsive system) to be integrated into a multi-level causal dependence framework. Then, the typical industry evolution scenarios are re-framed on the common ground of the causal network formalism. Subsequently, the framework is extended with a simple quantitative energy-based representation to formulate a qualitative case of how the scenarios could be formulated more coherently to avoid conflicting local optimisation objectives in pursuit of common higher-level goals. Finally, the entirety of the presented elements are brought together in a proposal to conceptualise an industrial system as a life cycle which exchanges matter, energy and information with its large-scale environment. The paper argues that such framing of the problem can pave the way to simplification of the problem of conflicting high-level objectives, by enabling a coherent understanding of the mutual dependence between a system of interest and the much more complex system of systems that is the aeronautical industry.

I. Nomenclature

<i>ACARE</i>	=	Advisory Council for Aeronautical Research (and Innovation) in Europe
<i>ATAG</i>	=	Air Transport Action Group
<i>ATM</i>	=	Air-Traffic Management
<i>EC</i>	=	European Commission
<i>EU</i>	=	European Union
<i>HP</i>	=	High-Pressure
<i>HPC</i>	=	High-Pressure Compressor

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<i>IATA</i>	=	International Air Transport Association
<i>LPC</i>	=	Low-Pressure Compressor
<i>MV</i>	=	Model Variable
<i>SAF</i>	=	"Sustainable Aviation Fuels"
<i>SFC</i>	=	Specific Fuel Consumption
<i>SR(I)A</i>	=	Strategic Research (and Innovation) Agenda

II. Introduction

In the wake of the recent global pandemic which made an unprecedented impact on the civil aviation sector, a number of industry actors have boosted the efforts to enable what they perceive as sustainable long-term future for the aviation industry: a state where industry growth and satisfaction of increasing demands of the travelling population is done without any harm to the natural environment. The pressure on the industry on the matter of its environmental footprint comes from the fact that in its current shape it is estimated to contribute to the anthropogenic global warming by the order of 5% [1], by far non-negligible contribution for a comparatively small industry with strong ambitions of further growth. The viewpoint of the community, which motivates the work presented in this paper, is well illustrated in the recent special issue of the review journal "Progress in Aerospace Sciences: Special Issue on Green Aviation". [2] In the introductory article, Platzer [3] makes the case for the unprecedented urgency for development sustainable aviation, arguing from the planetary perspective that this might be the last chance for the humanity to stop irreversible changes to the climate. Taking the full picture into account, it is inevitable to notice that such attitude implicitly conveys a problem of conflicting priorities - which some contributions from the same issue [4] have made explicit: the acknowledgment of a planet-level danger is somehow compatible with approaching the existence of the aeronautical industry - which contributes harmfully to the very same danger - virtually as axiomatic.

Coherently with the attitude described above, a number of industry roadmaps presented for decades by worldwide industry actors have been laying out different proposals for how the simultaneous growth and sustainability imperatives could be reconciled, and in satisfaction to all the involved stakeholders. Looking at the scenarios side-by-side reveals the problem to be one of necessity to overcome the inertia of various actors mutually entangled in delicate ways. The complicated nature of the problem can be illustrated with the following factors, to name but a few of the most representative:

- Practically the entirety of the current global fleet runs on fossil fuels;
- The fossil fuel combustion emits environmentally unacceptable species - either locally-toxic (notably NO_X) and/or contributing to the global greenhouse effect (notably CO_2 , NO_X , water vapour, particulate emissions, accompanied by contrail cirrus formation), of which CO_2 is of major importance as it is emitted the most and it has very long life in the atmosphere;
- The greenhouse gas effects depend not only on the absolute concentrations of the emitted gas, but on the emitting conditions, the altitude etc. - and these impacts are still difficult to estimate accurately;
- Despite being a relatively small industry, the civil aviation has become very important today for societies worldwide, either as economy driver, a GDP generator, or an indispensable utility, e.g. for people and cargo transport at remote locations;
- In the current global economic model being principally driven by market-based principles, monetary cost is at the core of business cases that must be made to drive any meaningful decision making;
- From the point of view of the airline industry, the major driver at the first-order analysis level is the direct operating cost, greatly influenced by among other:
 - Fuel/energy cost: the civil aviation history has seen multiple examples of fuel cost explosions creating powerful ripples throughout the industry;
 - Aeroplane maintenance costs: which influence the airliner's choice of the aircraft manufacturer and/or model for their fleet;
 - Crew training cost: same as the above;
 - Surrounding infrastructure: airport fees, access to energy-provision infrastructure, and other.
 - Acquisition cost: itself dependent on manufacturer's capabilities, the supply chain capacity, certification rules, etc.

Unsurprisingly, the industry-transition visions and scenarios have been numerous since the onset of the awareness of the industry's environmental impact at the turn of the century, as can be seen e.g. in the landmark European "Vision 2020" document from 2001. [5] Such visions of the future of the industry have been covering many, if not all, civil

aviation constituent subsystems, seen from various points of view: new technological concepts, different operational scenarios, transition to various new energy sources/carriers for low or zero in-flight emissions, externalised measures like carbon taxing and trading, or external emissions compensation for a "net-zero" effect, and combinations thereof. From the completely opposite side of the debate, various parties have been advocating outright reduction of the global fleet size and/or flying frequencies, arguing from the position that finance and innovation cannot solve the ecological impact of unrestrained growth (some notable examples from the public debate in France [6–8]), some of them arguing that international visions and roadmaps for the first two decades of XXI century in retrospect do not stand up to scrutiny in light of the climate-related goals. [9]

Recently, in an effort to consolidate the post-Covid recovery and the environmental optimisation, the European industry has focused towards a single major development strategy based on migrating the aeroplanes towards new energy carriers: the "Sustainable Aviation Fuels" (SAF) and hydrogen (H₂). It is worth underlining that this change in approach from a portfolio of potential strategies to a single approach is arguably the direct reflection of just how difficult it is to enable a full technological paradigm shift, that is to move away from the fuel-burning gas turbine *Tube and Wing* paradigm towards radically innovative solutions as discussed in many pre-Covid transition scenarios. (Kellari et al. [10] provide an elaboration on the concept of technological lock-in of the conventional aeroplane technological concept) No matter what the current avenue is for a given part of the industry, the identified conceptual problem which motivates the work presented in this paper is perceived absence of a consolidated common ground to discuss (i.e. evaluate relative to each other) all the different industry transition proposals, no matter what part of the industry they address, and from whose point of view.

The reality of the world is that constituent of a larger system must exist and operate as distinct entities. However, with the identified necessity for the current generation of engineers and/or decision makers to have higher-level awareness, that is to see beyond the boundaries of their system of interest - a need is identified for some form of higher-level perspective on the lower-level system in preliminary system design. This is translated into the need for a first-order analysis framework to transparently capture the system-level tendencies in which any constituent subsystem can be situated and evaluated coherently with its local surroundings, under full bottom-up, full top-down, or any in-between multi-level distributed decision-making scenarios. In turn, this requires a global trade-off framework where impact of the local contributions within the network can be expressed and mutually traded in figures of merit compatible with the global objectives or interest.

The objective of the paper is elaborate one such framework for first-order trade-offs. In particular, the work is driven in particular by the need by this research group to understand the place and the role of the aeroplane propulsive system - conventionally the (gas-turbine) engine - in this complex landscape. Despite being a clearly distinguishable and well-known aeroplane system, its links with the broader aviation industry in the context of the enunciated global objectives are non-trivial. To name but a few examples:

- It is the direct agent of transformation of the energy sources into polluting chemical species;
- Its cost is determinant to the aeroplane acquisition cost and the maintenance cost over its useful life span;
- Its architecture and size influence the adjacent subsystems and their contribution to the overall aeroplane performance (e.g. wing aerodynamics, non-propulsive systems efficiency);
- Innovative energy-efficient propulsive solutions such as hybrid-electric propulsion concepts would require provisions of materials that might be difficult to come by in large quantities, that is - might exert large external penalty on the natural environment.

The starting point for the framework development at hand is in the basic descriptive principles employed in engine preliminary sizing and design. These principles are abstracted these away from the said application, and the resulting framework is applied to describe systems which include both the engine and its surroundings, at various scales. The ambition for such framework is to elucidate the potential contradictions arising from actors optimising their subsystems locally for a global objective variable, and help pave the way for a more meaningful discussion and understanding of the roles of each individual actor in such collective endeavours.

To that end, the paper is organised as follows. Firstly, Chapter III presents a synthesis of industrial scenarios dedicated to energy transition and/or sustainable growth of the sector; some focus is put on the role of the propulsive system in the landscape of strategies. The synthesis is accompanied by overview of potential contradictions, challenges, and associated critical readings of such scenarios. Then, Chapter IV presents development of the abstract causal-network explanatory framework, which is intended to provide common ground for discussion and analysis of all the different constituent systems of the landscape. In Chapter V, the causal network framework is put to use by framing the prospective system-oriented transition scenarios against the common background. Finally, Chapter VI brings all the elements together firstly by elaborating a simple energy-based example application case, and then subsequently expanding it to

propose a life-cycle based description of industrial systems, be they the engine or the whole aeroplane, or any other system of interest.

III. State of the Art

A. Selected Scenarios for the Aviation Industry

The following summary presents a brief sample of historical and contemporary industry scenarios, in order to elucidate the representative development drives and interactions between involved actors. The review was rendered as compact as possible given the sheer amount and scope of the source material, which cannot be reasonably summarised within the confines of a single paper chapter. More comprehensive reviews of industrial transition scenarios can be found in Delbecq et al. [11], who provide aside from an in-depth review analyse the reviewed material against the backdrop of the Paris Agreement climate objectives. Additionally, Afonso et al. [12] presented a systematic review of

DOCUMENT	PUBLICATION YEAR (REVISIONS)	SCENARIO TEMPORAL HORIZON	FACTORS RELATED TO THE ENGINES / PROPULSION	ENGINE/PROPULSION CORRELATIONS WITH OTHER SYSTEMS
Group of Pers. 'Vision 2020' [5]	2001	2020	Impact on quality, affordability, and environmental impact. Improvements in environmental impact through fuel efficiency optimisation: engine cycle, structural materials, innovative components, alternative energy sources/carriers. Noise reduction through technology improvements. Disruptive technological concepts.	Natural environment; Airports and surrounding infrastructures; Operations; Manufacturing; Maintenance; Material supply chain; Large-scale economy.
ACARE 'SRA' [14-15]	2002 (2004, 2008)	2020		Natural environment; Energy production/supply; Airframe; Surrounding infrastructure; Manufacturing; Operations; Health and Safety; Electrical machinery industry; Preliminary design, modelling and simulation.
EC 'Flightpath 2050' [16]	2011	2020, 2035, 2050	Impact on society, local and global market, natural environment. Longer-term goals for disruptive technological (innovative components and materials) and operational solutions (e.g. in-flight energy harvesting).	Natural environment; Airframe and other onboard systems; Energy production sector; Enabling technologies (e.g. electrical systems); Synergistic technologies (e.g. artificial intelligence); Certification; Design/modelling/simulation; Broader market/business.
ACARE 'SRIA' [17-18]	2012 (2017)	2020, 2035, 2050		Natural environment; Energy/fuel production sector; Surrounding infrastructure/airports; Manufacturing; Digital systems; Design/modelling/simulation/experimentation.
Clean Aviation 'SRIA' [21]	2021	2035, 2050	Impact on environmental efficiency through energy efficiency and/or in-flight emissions due to the energy source used, mainly gravitating around alternative energy sources/carriers.	Natural environment; Airframe and other onboard systems; Energy production sector; Enabling technologies (e.g. electrical systems); Synergistic technologies (e.g. artificial intelligence); Certification; Design/modelling/simulation; Broader market/business.
EC 'Fly the Green Deal' [20]	2022	2035, 2050	Impact on environmental efficiency through energy efficiency and/or in-flight emissions due to the energy source used. Improvements through a wide variety of solutions, mainly gravitating around alternative energy sources/carriers.	Natural environment; Energy/fuel production sector; Surrounding infrastructure/airports; Manufacturing; Digital systems; Design/modelling/simulation/experimentation.
IATA '2050 Technology Roadmap' [22]	2019	2035, 2050	Impact on environmental efficiency through energy efficiency and/or in-flight emissions due to the energy source used. Improvements through evolutionary (near-term) and revolutionary progress (far term).	Natural environment; Airframe and other onboard systems; Airports and surrounding infrastructures; Communities near airports; Operators; Maintenance; Manufacturing (innovative tech. cost); Certification; Carbon offsetting technologies (market).
ATAG 'Waypoint 2050' [23]	2021	2050	Impact on environmental efficiency. Improvements pursued through evolutionary developments of gas turbine engines, and prominently new energy carriers and associated power trains.	Natural environment; Market and society; Energy production sector; Surrounding infrastructures; Airframe; Manufacturing; Maintenance; Certification; Operations; Airport communities; Automotive sector. (tech. development synergy)

Fig. 1 Summary of the sampled industry projection scenarios with focus on changes related to propulsive systems and identified impacts those changes have across different systems covering the aeroplane and the wider industry landscape.

industrial approaches to lowering the future environmental impact. The scenarios and the information relevant to the work of this paper are summarised in Fig.1, all of which are elaborated in the following.

1. European Industry Development Incentives Since 2000

The European aviation industry has undergone major consolidation efforts at the turn of the century, in big part carried by gathering of historically disjoint national industrial actors around common goals and agendas for the European industry. The landmark document which set the stage for major developments in Europe was "**Vision 2020**" [5]. The report, presented by the group of high-level personalities from the sector, gave their vision of what the European industry would look like in year 2020, with Europe as a global player on the civil aviation market. This document led to creation of the Advisory Council for Aeronautical Research in Europe* (ACARE) in 2001, whose advisory role is maintained until this day. The prospective industry developments encompassed by these initiatives is comprehensive in:

- Technical scope: covering the aircraft technologies, operations, air traffic management, airports, energy sources;
- Objective variables: covering performance, safety, quality of service and comfort, market performance and environmental impact.

Subsequently, a "**Strategic Research Agenda**" (SRA1) [13] was presented in 2002, developed to guide the coordinated research and development in Europe (EU), and to enable the transition of then-current aviation industry towards the then-future state elaborated in the "Vision 2020" document. A comprehensive summary of the SRA1 would be fully relevant to the work presented in this paper, but would take excessive space to meaningfully present in its entirety. This is particularly so because - as will be briefly elaborated further below - the agenda has been undergoing several updates throughout the years, as have the base "Vision" documents. A brief zoom will therefore be made on the current system of interest - the engine - to elaborate how it was perceived/understood in its environment.

The SRA1 document saw the engine as a contributor to the quality and affordability goals of the industry. More interestingly, a distinct engine contribution to the environmental impact of the industry was identified: of the overall projected 50% reduction in CO_2 emissions through fuel burn reduction, the target for the engine efficiency improvement was 15-20%. Emphasising the well-known difficulties with simultaneous optimising for both CO_2 and NO_X reduction of gas-turbine engines, prospective engine improvement pathways were outlined: conventional evolutionary improvement in engine pressure ratio (optimising thermal efficiency) and bypass ratio (optimising propulsive efficiency). These would imply use of more advanced engine materials and system- and component-level design alike. (including innovative combustion technologies, intercooled-recuperative engine cycles, etc.) Alternative (combustion-based) energy sources/carriers were equally evoked, such as hydrogen, methane or bio-kerosene. The engine would equally optimise for external perceived noise reduction. Environmentally-friendly manufacturing, maintenance and disposal processes are evoked for all the aeroplane-related products, encompassing the engine as well. It is important to mention that the engines were also pinpointed as an important element of EU's market performance, with stated 40% share of the global commercial jet engine market of the time.

In 2004, a new **SRA (SRA2)** [14] was presented with the same underlying approach as its predecessor, linking the individual optimisation of engine performance with important contribution to the overall environmental impact reduction. Potential development pathways included improved engine efficiency, capability to use different fuels or power sources (such as fuel cells), including hydrogen or synthetic/bio-kerosene, different aeroplane operations, for instance taxiing in and out by means of electric APU (auxiliary power unit) rather than using the engines. CO_2 reduction would still be enabled by evolutionary performance enhancements, whereas the simultaneous NO_X reduction would depend on the enabling technologies such as combustion chambers and fuel injection systems. Efficient integration of the ultra-high bypass-ratio engines into the airframe was seen as enabler for steep takeoff and approach, which would minimise the airport community noise impact. Additionally, in the wake of the 9/11 terrorist attacks on the US, which visibly marked the development of these agendas for increased security, engine was also seen as a factor in optimisation for higher airline security. Possible changes to engines to protect the aircraft from potential short-range missile attacks would require inclusion of flow mixers for the bypass engines in order to reduce the heat signature of the aircraft. The SRA2 document is remarkable in that it explicitly acknowledges that the different objective variables of market-, safety-, environmental and other high-level goals can work against each other in optimisation, and that compromises between these must be sought.

In 2008, an addendum to the **SRA (SRA_Add)** [15] was presented. Motivated by a need to move away from kerosene in light of the political-economic development of the time, the document stated that more revolutionary engine-related solutions might need to be researched in parallel with the conventional/evolutionary improvements. The revolutionary

*Later, and until today: Advisory Council for Aeronautical Research and Innovation in Europe

avenues would include use of hydrogen engines, liquid natural gas/methane or even nuclear energy. It is emphasised that such solutions would demand new technologies for the aeroplane as well as the surrounding infrastructures.

2011 saw publication of another widely-known document: "**Flightpath 2050: Europe's Vision for Aviation**" [16], the successor/update to the "Vision 2020" document published 10 years earlier. The new document provides a mid-term status of the "Vision 2020"-driven developments, asserting establishment of EU as a strong global aviation industry actor, and extending the vision for the industry towards the long-term horizon of 2050. As it was the case before, the document is profiled through notional goals for society and market, industrial leadership, environmental impact (with energy supply as explicit decision variable this time) as well as safety and security. From the engine/propulsion point of view, the document sees hybrid-electric propulsion as present in the hypothetical 2050 market. The engine design process is seen as performed in unison with everything from airframes, components, fuels, including infrastructural, manufacturing and operational procedures.

On the basis of the new vision, a new "**Strategic Research and Innovation Agenda**" (SRIA) was presented in 2012. [17] From the engine perspective, its determinant role in the emissions performance through energy efficiency improvement and use of innovative technologies (e.g. to keep the NO_x emissions in check) is maintained. Engines as cutting-edge products offered to the global market by the EU industry is still present. New engine materials are evoked, specifying in particular that they would need to be highly damage-tolerant, high temperature tolerant, environmentally-friendly in terms of manufacturing, re-usability and scarcity. Potential use of nano-technologies is mentioned, noting the impact it could have on human health and safety. Engine as potential agent for in-flight energy harvesting for the electrical systems is evoked. The electrical systems are correlated with necessary developments of electrical storage and transformation, actuation, high-power control, electrical conduction and heat treatment. Capability to support developments by high-fidelity multidisciplinary simulation of virtual engines is evoked. Increased adaptability is mentioned as an enabler too, relying on intelligent sensors, controls and actuation and advanced health monitoring and associated maintenance, which would work to reliably reduce safety margins and result in improved performance across the lifetime of the engine. Integration of the engine into the airframe is still present as crucial element of the overall drag optimisation of the aircraft, to the level that engine/propulsive system will grow to become an integrally designed and optimised part of the entire aeroplane, in full synergy with the airframe and other onboard systems. Propulsive solutions like boundary-layer ingestion propulsion, distributed propulsion as well as smart materials and morphing structures are evoked, all alongside the options for well-advanced conventional gas-turbines. In terms of the pollution managing, knowledge of the engine exhaust emissions is evoked as something that would be fully known in the considered optimisation time frame, and to be included in the global European environmental impacts tool. Use of sustainable aviation 'drop-in'[†] fuels is presented as predicated upon development of innovative production processes. Engine technologies are also correlated with research capabilities, including methods and tools for simulation and performance analysis. Finally, the CO_2 reduction impact at various milestones (2020, 2035 and 2050) were broken down, and the engine contribution to the overall impact reduction of the industry, through energy efficiency improvement, was clearly given alongside (for reference) contributions to the efficiency reduction by the airframe, air-traffic management and surrounding infrastructure, and the non-infrastructure-related airline operations. The **2017 update to the SRIA** [18] document presents the same view, describing a diverse portfolio of technological options for the propulsion, enabled by various possible associated energy sources, innovative materials, operating procedures and integration scenarios.

Following the Covid-19 global pandemic, another rework of the Visions and the agendas was recommended, this time arguing from a position of strong and explicit focus on climate impact reduction, and carbon neutrality in particular, with affirmation of the crucial role the airline industry plays for the modern society. [19] A full revision of the "FlightPath 2050" document in line with *The Paris Agreement* and *The European Green Deal* was carried out, resulting in the current incarnation of the ACARE vision for the EU aviation, titled "**Fly the Green Deal**". [20] The new vision relies in big part on a variety of energy sources/carriers, prominently including the sustainable aviation fuels, but also electricity and hydrogen. It is emphasised that these are fully integrated into the broader energy sector, relying on the surrounding infrastructure, airport readiness to support these development, as well as sufficient provision/supply of these energies, assuming their environmentally-friendly production based on renewable sources. Digital transformation is again put in correlation with capability to explore comprehensive design spaces for propulsion systems by numerical and experimental high-fidelity methods and appropriate experimental test facilities for the integrated systems.

[†]Fuels directly compatible with the existing aeroplane and engine technologies.

2. European Public-Private Partnerships

The frameworks presented in the previous subsection incentivise research and development at lower maturity levels, whereas further maturation and testing of technologies at higher levels would be carried out under joint public-private initiatives such as "Clean Sky", "Clean Sky 2", or currently "Clean Aviation". For the sake of brevity, only the **SRIA elaborated by the "Clean Aviation"** Joint Undertaking in the wake of the Covid-19 pandemic will be presented here. [21] The ambition of the document, akin to the ACARE strategic agendas presented in the previous section, is to elaborate on the pathways and scenarios that need to be pursued in the framework of the Joint Undertaking in order to materialise the aviation sector contribution to *The European Green Deal* high-level objective: climate neutrality for the the EU by 2050.

The engine/propulsion point of view is prominent in analysis of this agenda, since the explored pathways all have propulsion and power technologies at their core, with numerous dependencies across the spectrum of aeroplane adjacent systems, life cycle phases, involved actors, surrounding infrastructures, and energy sources. Moreover, as opposed to the previous, notably pre-Covid, ACARE agendas, these particular developments are unambiguously relying on new energy sources/carriers as enablers of climate-neutrality. The new energies are consistently labeled as clean and/or climate-neutral, emphasising the importance that these do not produce upstream climate impact. The SRIA breaks down the technologies into three groups, aiming to mature them for short-medium range applications in the near-term (2035 horizon) and eventually for the long-range applications as well (2050 horizon), to achieve full climate neutrality of the industry. The three groups are hybrid-electric and full-electric architectures, ultra-efficient thermal propulsion systems, and disruptive hydrogen-powered architectures. The document mentions that the current modelling techniques are not necessarily apt to design and evaluate the innovative propulsion solutions (e.g. propulsion distribution). Hybridisation/electrification of propulsion, which aside from zero in-flight emissions can enable energy savings by introducing new degrees of freedom in operation would require innovative high-power, low weight, high-efficiency electrical components and systems. Longer-term ultra-efficient propulsive systems would rely on smarter engines with variable geometry with AI-based control systems that learn, adapt, and provide real-time operational optimisation. Light-weight materials are another necessary enabler, as well as innovative combustion technologies. All of the new propulsive scenarios will inevitably pose challenges for certification, which is why the necessity for inclusion of the engine manufacturers and certification authorities from the early design phases. An emphasis is put - for the engine and other aircraft systems alike - on necessity to evaluate all the new energy sources, materials and technologies from the life-cycle point of view, with focus on design, manufacturing, operations and disposal alike on the road to fulfilling the global goals. It is emphasised in the document that these low/zero-emission (supposedly in-operation) sources will be more energy intensive to produce, and available in limited quantities but that nonetheless, innovations in propulsion may open new business scenarios.

3. IATA Aircraft Technology Roadmap to 2050

In 2019, the International Air Transport Association (IATA) presented a review of candidate technologies across the spectrum, which could contribute, but not be sufficient by themselves, to reduce the airline industry climate impact by 50% relative to year 2005. [22] The progress was seen as evolutionary until year 2035, followed by disruptive solutions which would bring the step change. Evolutionary engine technologies would include further gas-turbine improvements based on ultra-high bypass ratio turbofans supported by advanced components such as fans and combustion chambers. The revolutionary options would range across the design space, encompassing open rotors, boundary-layer ingestion propulsion and various hybrid- and/or electric options with different airframe morphologies and integration scenarios. Unsurprisingly, the document cites interactions with the surrounding infrastructures that are necessary to support the eventual technological disruptions. Airports are connected by the need to provide high-power electricity supply for electrical power trains, as well as for potential higher community noise impact and lower cruise speed impact of use of open rotor engines. Furthermore, it is emphasised that direct operating cost cannot be prohibitive for operators, especially at potentially high purchase cost of innovative technologies. Maintenance is seen as a factor which might favour electric technologies over thermal power systems. The risk of new technologies can be seen from the manufacturers point of view as well, whose cooperation is determinant for launching new programs. New certification processes are evoked. Close cooperation among all the involved stakeholders is emphasised if enough lead time is to be given to the surrounding airport/airspace infrastructure to prepare for the new technologies. Finally, sustainable aviation fuels and market-based carbon-offsetting measures are indicated as cheaper than implementation of radically new technologies, but might have limited supply so new technologies remain necessary to reduce the need for these.

4. Air Transport Action Group Scenarios

Finally, a prominent document "**Waypoint 2050**" [23] by the aviation sector experts grouped under the banner "Air Transport Action Group (ATAG)" presented their vision on how the industry can transition from the current state to meet the 1.5° goal of the Paris Agreement by 2050. The presented scenarios, even with the most optimistic technological advance, rely in greatest measure on "sustainable aviation fuels" and market-based measures for carbon offsetting. The innovation in propulsion relies on energy/power hybridisation and utilisation of hydrogen as energy carrier. Additional technological routes for propulsive system improvement include further thermal engine efficiency increase, enabled by innovative combustion technologies and innovative materials. Certification difficulties for innovative systems are emphasised. Hybrid- and/or electrically-powered aircraft provoke a spectrum of interesting points. The document states that such aircraft are going to be quieter, which can lead to more flights from city airports given the lower community nuisance. Challenges are evoked in scaling the hybrid/electric technologies from smaller to larger vehicles. CO_2 footprint of raw material extraction for batteries is evoked. There is a mention of the limitation of electricity to short-haul flights because batteries don't lose weight, which puts major new constraints on landing systems and structures. Great electricity demand is evoked, claimed to be of order of 0.1-1% of global electricity demand in 2050. For operators, an impact can be seen in increased turnaround time for recharging, which can impact the number of operating cycles and the revenue. Manufacturers can also experience pressure for higher energy density materials and high-temperature superconducting materials. Concerning the introduction of hydrogen as main energy carrier, it can incur higher costs of the propulsive system, including its maintenance cost, at least in the introductory years. There is a mention of uncertainties around the necessary airport infrastructure modifications and associated cost. Hydrogen production is expected to be sustainable ("green"), which is today by far not the case. The non- CO_2 effects on the climate are still not sufficiently well known, so its necessary to understand them better, especially as hydrogen propulsion emits large amounts of water vapour. Among multiple actions that the group recommends to be incentivised concerns propulsion, indicating that there is not yet enough maturity in the field; in that domain, one recommendation also calls for synergy with the automotive sector.

B. Discussion of the Scenarios

Prior to discussing the overwhelming variety of possible scenarios put forward by the industry, a glimpse at similar proposals from the research community is provided. Ansell [24] reviews the sustainable energy carriers for aviation, arguing strongly about how aviation is an indispensable enabler for human connection, well-functioning economy and social development, while at the same time pointing out that viability of the sustainable energy carriers depends strongly on developments outside of the aviation sector. In complement to that example, Jensen et al. [25] argue that the optimistic prospect for "net-zero" emissions by the US aviation industry by 2050 is mainly predicated on the "sustainable aviation fuels" and employment of market-based (that is, external) measures. Aside from relying on a solution which is not managed by the industry itself (e.g. aeroplane technology and operation are, whereas energy production is not), the real sustainability of such solutions is not as certain as the proponents claim. Köves and Bajmócy [4] provide a critical reading of the "sustainable growth" hypothesis based on sustainable energy sources and bio technologies, arguing that different viewpoints among contributing stakeholders where all are driven by the growth imperative - cannot solve the problem at hand, and a de-growth point of view might need to be assumed in order to enable meaningful conversation. In complement, in a critical analysis of the sustainable aviation fuel impact on land use, Becken et al. [26] claim that reliance on sustainable aviation fuels not only does not contribute to solving the sustainability problem - but it might undermine it, and that the public debate and industry roadmaps do not recognise this. A critical review by Beevor and Alexander [9] argues that all the high-level climate targets laid out for 2020 were missed by the industry. Traces of the potentially dissonant high-level goals of such scenarios can be seen in ambition of the ATAG for the aviation to contribute to keeping the global temperature rise at the 1.5 degree threshold by 2050 in the world where for the first time ever a short overshoot of the mean global temperature of 2 degrees was measured for the first time in history in late 2023. [27]

Keeping the focus on the new energy carriers pathway, the "net zero" scenarios prominently advertised by various industries rely on the assumption that " CO_2 in" simply compensates for " CO_2 out", whereas the mechanisms underneath are more complicated as the gases are emitted at high altitude whereas the purported compensation efforts are made on the ground; this is without even mentioning the extra energy potentially necessary to capture carbon. This is a trivial but rather telling indicator of the strong non-linearity of the whole dependency network between various industry constituents, where global optima can only be reached when the problem is addressed accordingly, and with sufficient transparency among the actors who partake in the task.

The problem at hand is therefore not only a matter of academic pedantry, but of basic coherence without which the core global problem arguably cannot be addressed, let alone solved. One aspect is that the aviation industry - itself a component in a vastly bigger industrial system - is divided among many actors who are in charge of a certain component, each actor with their own objectives and agendas, in dynamics where collaboration and competition often overlap. Where goals and ambitions are quantified for the various actors and the contributions to be made by their respective systems and/or operations, the overall net effect tends to be broken down into simple aggregate of the respective subsystems/operations effects, such that everyone can locally optimise whatever objective of their individual interest. The ambitions for massive change of the energy carrier seem to take many factors for granted, the most prominent of all being that the aviation is but one industry which will compete for SAF and H2 provisions in a world where these are either:

- By far not abundant: e.g. the SAF are in strong competition with agricultural land use;
- And/or not really sustainable to produce: e.g. H2 production is currently very CO_2 intensive, and due to a very low chain efficiency of the H2 production a massive amount of currently non-existing renewable energy would need to be supplanted to cater to a potential transition of the massive industries;

Those factors constitute a major risk from the point of view of attaining the indispensable sustainability objective, which begs the question of what happens in case these solutions do not prove to be the right way to go?

Upon this background, Chapter IV focuses on development of a simple descriptive framework for coarse-graining systems into finite arbitrary number of sub-parts whose individual ontologies (the objects and relations used to describe them) add up to the unitary ontology of the higher-level emergent system. By leaning on system representations in form of simple causal networks, a broader meaning of the boundary the system shares with the environment/adjacent systems is derived in Chapter V, and the global sustainability problem is framed as search for equilibrium between:

- Matter, Energy and Information exchanged across this boundary,
- And the Matter, Energy and Information flows of the global environment within which the investigated system is situated.

IV. The Analysis Framework

A. Abstract Network Representation of Systems

The proposed explanatory framework is directly based on the principles elaborated by Negreiro and Joksimović in [28], which are summarised in the following for application in the current context. The framework leans on the basic

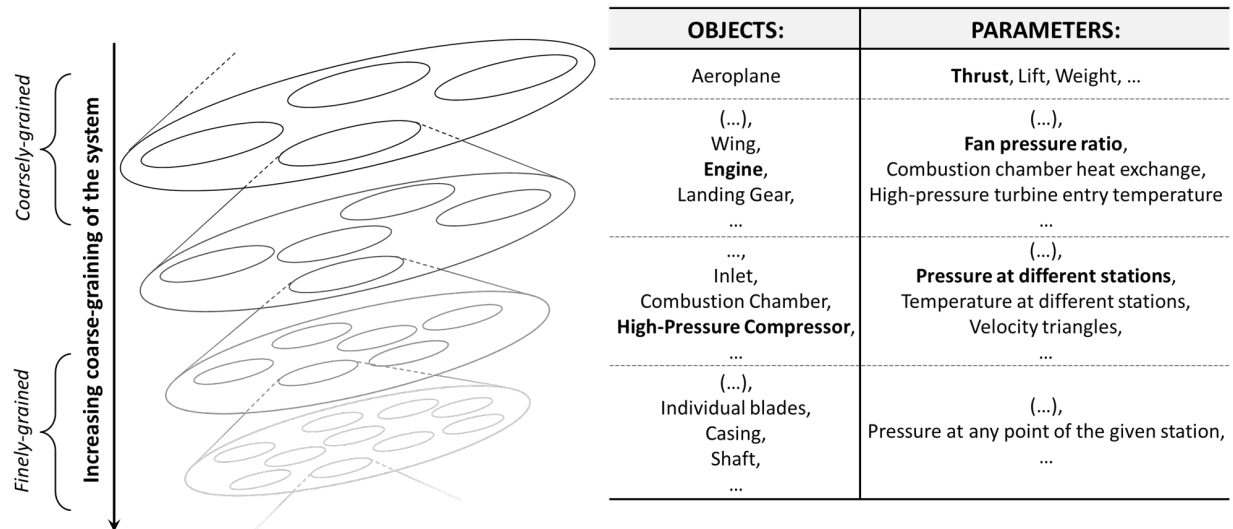


Fig. 2 Principle of system coarse-graining (left), with example applications on physical objects (center column) and parameters used to model objects at different levels (right column); note that the two columns are not in direct correlation. Based on [28].

hypothesis that any system of interest can be represented as an arbitrarily *coarse-grained* mathematical model (i.e. a hypothetically infinite reality is reduced down to a finite number of parameters). From that starting point, the framework is derived as follows:

- 1) The model (governing equation system) is a reflection of the granularity of the modelled system, that is - any piece of reality of interest can be defined as a system by "coarse-graining" it (Fig.2) into a set of correlated parameters that determine its state.
- 2) Every system element can be further coarse-grained in its own right, and analogously every system can be considered to be one such element in a higher-level coarse-grained system.
- 3) Given the necessity for the underlying model equations to be determined in a complete and consistent way, certain number of the coarse-grained parameters will be necessarily available as input to the designer, whereas the other ones will be calculated as output. The mathematical system is agnostic to any particular input-output structure of the equation system.
- 4) If a causal flow direction is attributed to the correlations between the system parameters, where the state of inputs will be considered to "cause" the state of the output parameters, the correlations can be drawn as a simple causal network where the parameters are the nodes and the relationships between them are the edges.
- 5) Within that network, the distinction is made between **Data**-type parameters and **Model-Variable**-type parameters in that the Model Variables have both upstream and downstream causal dependencies, whereas the Data have only downstream causality. (Fig.3) In other words, Data-type parameters do not have any causal history, which is a very important takeaway for the current purposes.
- 6) Nevertheless, separation of the parameters into Data and Model Variables subsets need not map directly onto a prescribed default input-output structure; this feature is instrumental in bringing about different ways to go about designing and/or analysing such coarse-grained models.
- 7) For the sake of simplicity of this introductory elaboration, all of the current developments will be restrained to steady-state analysis only, i.e. with no time-evolution of the model state will be considered. However, it bears no impact on the overarching message of this paper and of the framework development at hand.

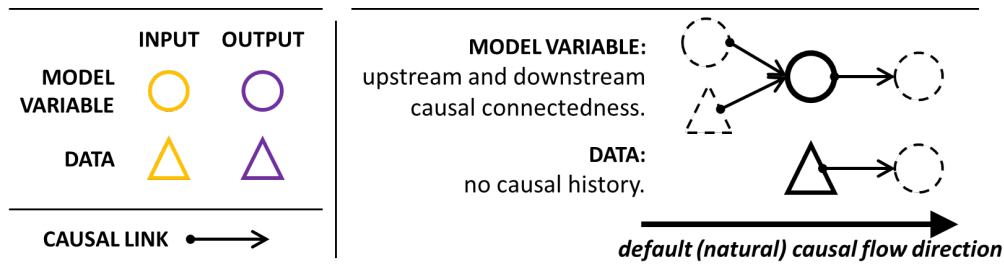


Fig. 3 Depicting *Data* and *Model Variable* parameter types from the point of view of their causal relationships with the other connected parameters. [28]

With these basic notions in hand, it is now possible to take a closer look at the system of main interest to this work: the civil aeroplane engine. Taking a preliminary-design-level engine performance model in the classical form thermodynamic equation system, the developed principles can be employed (Figs. 2 & 4):

- 1) The equations are a coarse-grained representation of this highly complex system, represented by a, practically speaking, handful of parameters such as temperature, pressure, entropy and the derived properties at distinct engine stations. (Fig.4-1)
- 2) Every one of these parameters can in principle be further coarse grained, e.g. the respective flows can be broken up into sub-flows, which is ordinarily done when - on the basis of the previous thermodynamic results vanes and turbomachinery blades are designed, with each local flow having its own local temperature, pressure or size parameters.
- 3) In the coarsely-grained representation of engine thermodynamic model, the Model Variables will be the ones that are meant to capture the system behaviour (e.g. temperatures, pressures), and in the default equation configuration where the causal flows are aligned with the causal flow observed in nature (Fig.3) these will be calculated as model outputs. In turn, the inputs will be parameters such as the air inlet atmospheric conditions, nozzle cross section areas, assumed power transmission efficiencies and duct pressure losses, all categorised as Data.
- 4) While the fully determined model equation system will simply correlate all the parameters, in the default-causality

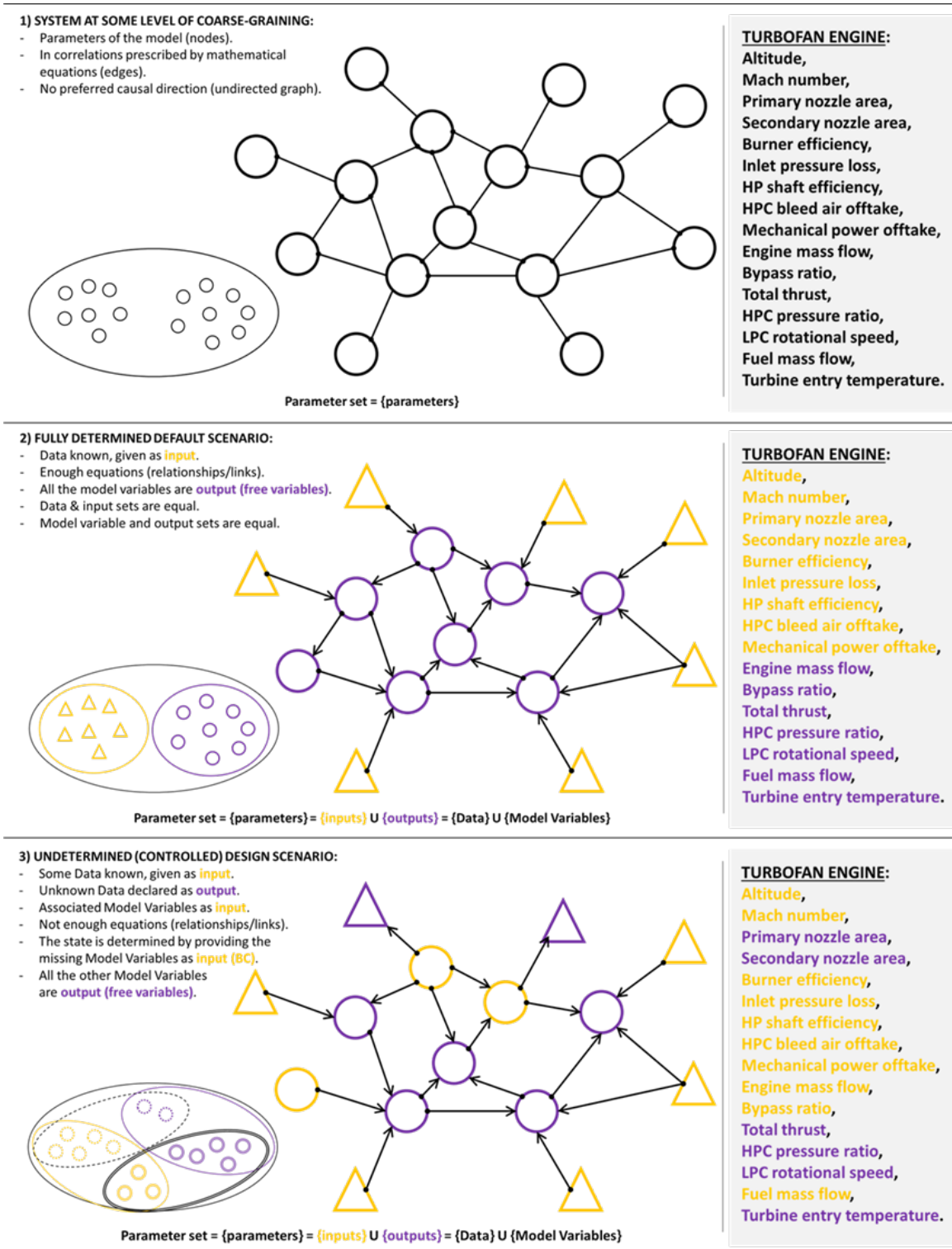


Fig. 4 Coarse-graining and causal network definitions (based on [28]) given on a simple turbofan engine illustration case: 1) coarse-graining and parameter correlations; 2) Data representing the input (yellow) and Model Variables the output (purple) for a fully determined system; 3) Imposing a desired state and inverting the causal flows to calculate the unknown Data.

mode of calculation the Data will be input for which the Model Variables will be calculated to fully determine the state of the system, i.e. its performance. (Fig.4-2)

- 5) However, when a new engine is designed, the designer will have at least a vague idea of the architecture type to define, but will commonly not know the values of the Data. This often necessitates numerous iterative calculations in order to try to deduce their correct values which could be then used in subsequent performance modelling. This iterative procedure consists of two distinct causal calculation cases:
 - a The case of **inverted causality** (with respect to the default): where a desired state is imposed through Model Variables, and in turn the Data values that will produce that state are calculated;
 - b The case of **default causality** (aligned with natural causality flows): where the above-calculated Data results are fed back to the model, and the response of the Model Variables is explored across the design space. (Fig.4-3)

This simple development, representative of the first-order level design practices, is informative about the role of Data in such system modelling. The definition of Data as a parameter that does not have any causal history within the model, implies that it represents the interface of the modelled system to the parts of the real world with which the model is not concerned. For example, an engine model can include a bleed air mass flow offtake at the compressor (in reality dedicated to feeding secondary onboard air systems) in form of a Data parameter, as it is commonly just a value prescribed by the user. Depending on user's knowledge/experience, that value can - but does not have to - be representative of what a real-life secondary air system would require from the engine at given operating conditions. If the engine performance depends on that value, as it is the case, the designer will be limited with the available knowledge about the values the Data could or could not assume for a given model state. On the other hand, if a model of the secondary system were attached to the engine model, the same parameter would become a Model Variable, itself correlated from each side with the secondary system and the engine models, respectively. From the point of view of the engine, the knowledge border towards the "external world" would be pushed much further out, and the designer could evaluate the compressor bleed air flow value much more meaningfully.

Therefore, if a designer disposes with an elementary model of a system of interest, elaborated according to the principles listed and exemplified above, with full control (e.g. via a modelling interface) of the consistency and coherence of the causal flows in the resulting network, the following inferences can be drawn:

- Any subsystem could be represented by further coarse-graining of the parameters of interest, and by subsequently collecting these parameters into a subsystem of interest;
- Any system could be inserted into a larger system (of systems) of interest by plugging it into the other adjacent models that follow the same rules;
- At any granularity level, when modelling any system of interest, Data-type parameters represent the **boundary** that divides the model into the part of the real world that is meant to be captured by the model and the part of the real world that is effectively neglected by the model - **the environment**. Given the fact that Data-type parameters do not have in-model causal history, they also represent the boundary of knowledge about the modelled system.

For a comprehensive presentation of the different ways to grow the causal network, and the relation of these mechanisms to system design, the interested reader is referred to the companion paper by the same authors. [29]

B. External Pressures on the System

The historical engine development has been driven by physical performance requirements, which can be represented at first-order level by the fuel consumption. While significant historical progress has been achieved in optimising both the consumption and the polluting emissions through fuel flow reduction, progress has been made in other correlated performance indicators such as cost or noise. Recent years have seen emergence of additional requirements on the fuel (or energy) performance, in efforts to reduce the greenhouse gas emissions of the aeroplane. All of these, since the onset of the jet era at least, have been done without any profound changes to the engine architecture and the way it interacts with its environment. In civil aviation design space, the optimisation trend was inseparable from the gas-turbine engine, i.e. the turbofan architecture in particular. In light of the context behind this work, the question emerges of how to correctly manage the requirements and constraints on the system in preliminary design of a radically different propulsive concepts.

Looking back at the big-picture backdrop developed in the State of the Art chapter, it is evident that any newly emerged requirements on the propulsive system trace back to the pressures on the industry to reconcile its environmental impact with the desire to maintain, if not increase, its size. Various advocates on the both sides of the debate, be it those advocating pursuit of the growth or those calling for inverting the trend, will lean on their respective ideas of what the

real needs of the citizens are, the real requirements and real constraints the aviation: social needs, speed, distance, cargo, medicine, rescue, sober travelling...all of them prone to contextualisation in their own right.

The main thesis of this paper is that the engine causal-network modelling formalism presented in the previous section for purpose of understanding engine preliminary sizing process can just as well be employed to represent larger-scale systems, be it the whole aeroplane, or a fleet, or the industry as at large. If the aviation industry was to be represented using the developed abstract formalism, it would in very rough terms mean:

- 1) Assuming the industry to be an object;
- 2) Coarse-graining it into a number of parameters that can be correlated into a consistent deterministic equation system describing the industry state as a whole;
- 3) Dividing these parameters into two types: the ones without causal history, the Data (default state: input) and the ones having a causal history, the Model Variables (default state: output);
- 4) Calculating the system performance based on the available knowledge and optimising lower-level systems within these high-level boundaries.

While it might be straightforward to see what the various constituent parameters of the coarse-grained airline industry object would represent - e.g. airports, global aeroplane fleets, air-traffic management, catering, maintenance infrastructure - it is more interesting to look at what the Data parameters are from that point of view, and what the Model Variables are. In other words, what is the airline industry system boundary (represented by the Data), what are the Model Variables that can be controlled, and what are the free Model Variables which represent the system performance caused by the above two? As a reminder, if a system can be represented as a causal network, it can arguably be manipulated according to the principles summarised in Fig.4.

It could be seen as a trivial question at face value, but answers and their further implications could hide some valuable insights. Figure 5 (above) provides a qualitative visual overview of the "system as a coarse-grained causal network" idea applied to the airline industry. In this simplified picture, some examples could be pinpointed; these are necessarily going to be out of context, as an exhaustive list would overwhelm reasonable limitations of a single paper. For an airliner, the Data would be e.g. the passenger demand, the material provisions to produce and maintain the underlying systems and operations, the weather/operating conditions, the available aeroplane technology. The control Model Variables would be e.g. the investments made into the industry operation (workforce, infrastructure, operations), or the operating procedures of the different subsystems of the industry. The free/resulting Model Variables would be e.g. the revenue generated by the industry, the passenger satisfaction, the emissions/environmental impact of all the operations.

Equivalently, pressures on the aeroplane engine (designers/manufacturers) can be painted in the same colours (Fig.5, below): Data parameters would represent e.g. the engine size admissible by the wing ground clearance, or the needs of the adjacent accessories that draw mechanical power, or the available materials to produce the engine components. The

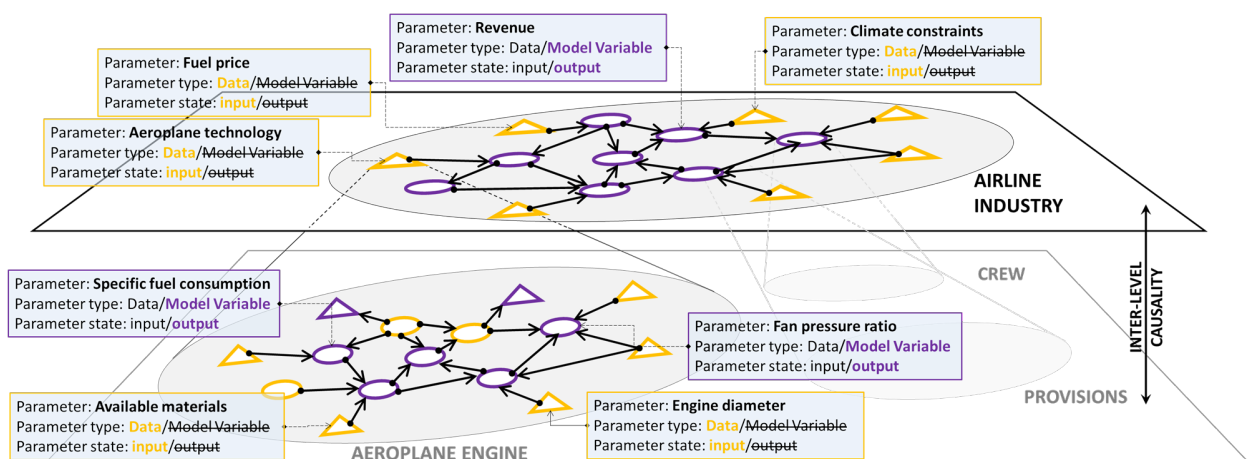


Fig. 5 Recurrence of the system representation at different coarse-graining levels, in line with the illustration from Fig.2: the level above representing the airline industry, and the level below representing the aeroplane engine. Examples of Data and Model Variables interacting between two levels, which are determinant for what can be known about the systems, and how the different levels can influence each other.

control Model variable would be e.g. the engine fuel flow in operation or the profit margin in sales. The free resulting Model Variables would be e.g. the engine performance parameters such as the specific fuel consumption, or the engine manufacturing cost, its weight, etc.

The above description is representative of the default calculation case as defined in the previous section, which does not explicitly consider whether certain parameters are formulated as requirements or constraints on the system under consideration. That aspect remains in the broader scope of the current work; in this first approach such details will be omitted, as it is not determinant for conveying the basic ideas behind the current development. For the moment, it suffices to postulate that the requirements can be identified with the control Model Variable parameter types, whereas the constraints on the system can be identified with the Data parameter types.

Before proceeding to demonstrating how this description can be employed to develop more comprehensive understanding of the industry tendencies and of the role of different subsystems such as the engine can be articulated using the current setup - a closer look at the different aviation industry adaptation scenarios will be given using this framework.

V. Adaptation Strategies Reframed

In this chapter, the range of industrial strategies sampled in the State of the Art chapter will be revisited in order to gain more insight on relationships between actors and systems by employing the developed formalism. The key elements of the strategies will be divided thematically into distinct blocks, each presented in form of a causal network whose different levels represent points of view of the respective stakeholders governing the represented system. The following blocks are outlined:

- Technology,
- Operation/ATM,
- Enabling infrastructures,
- Energy sources,
- Measures external to the aviation industry.

A. Technology

From the point of view of the big picture painted around the aeroplane propulsive system (the engine), the most intuitive development pathway in light of the global optimisation problem is to seek higher efficiencies through technological improvements. For decades, the common proxy variable for optimising both the economic and environmental performance of the civil aviation has been the fuel burn. For easier categorisation of concepts with theoretical promise to enable step change in energy efficiency, in a first approximation the technological trends can be categorised into whole-vehicle level concepts and subsystem-level improvements. The latter can revolve around different subsystems, for instance the environmental control system evolution or tendency to electrify different power systems (the "More Electric Aircraft" paradigm), or the propulsive system.

A more thorough review of the innovative system design space, presented from the point of view of function-to-form mapping (itself related to the causal-network framework) has been presented in a separate work by the authors of this paper. [30]

1. Vehicle-Level Technology Evolution

In this subsection the idea of the whole-aeroplane innovative concepts is considered, such as for instance NASA's "N3-X" distributed-propulsion flying wing concept [31], or TU Delft's "Flying-V" [32]). An example of aeroplane-level, or strictly speaking airframe-component improvement can be the folding wingtips of the Boeing 777-*x*. Structural material improvements have been prominently seen with introduction of composite-material structures on Boeing 787 or Airbus A350.

Fig.6 presents a very simplified picture of the causal dependencies across different level describing the whole-aeroplane technology optimisation potential. The figure is structured according to the notional coarse-graining layers of the aeroplane - aeroplane, its systems, their components - which is itself embedded in a broader environment. The representation of each layer is made as if it were seen from the vantage point of the actor governing the system being observed at the given level. For instance, the component designer sees the relevant parameters governing the state of the component at hand. The aeroplane features such as the wing structure adjacent to the wingtip, or the even higher-level airport constraints, or maintainability requirement are seen as Data type parameters at the component level, as they

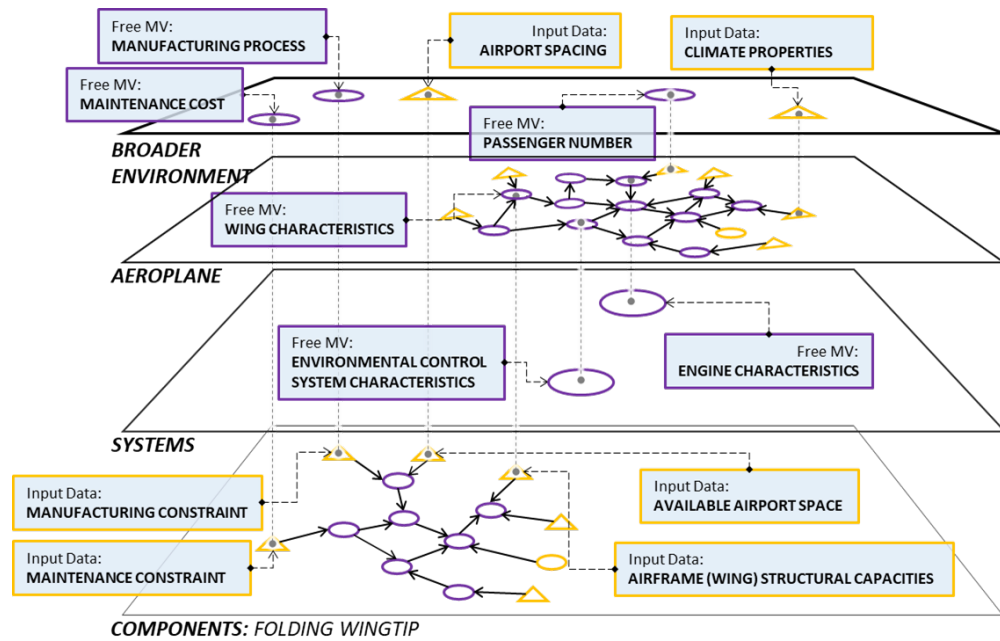


Fig. 6 Aeroplane-level technology adaptation scenario illustrated from the causal network point of view: case of introduction of a folding wingtip onto an existing aeroplane.

are out of component designer's causal influence. The aeroplane level is presented as more fine-grained in its own right, since from the point of view of the whole-aeroplane designer it will consist of a wealth of details describing the aeroplane. The aeroplane design will itself be constrained by other higher-level instances, e.g. an instance such as the passenger number, here represented as a free Model Variable seen from the point of view of the airliner. Another example is the climate characteristics that are represented as Data, as they are a constraint that is beyond the control of any designer. In summary, each of the presented coarse-graining levels can be identified with an actor in charge of a system at that level; the Model Variable parameters ought to transparently describe the model at hand, here the entire aeroplane, while the Data parameters cover "interfaces" with an upstream dependency, such as surrounding systems, natural resources, etc. The formalism presented in Fig.6 will be used throughout the remainder of the text, i.e. when elaborating the subsequent thematic blocks.

2. Propulsive System Technology Evolution

With subsystem-level improvements the objective is to focus the optimisation efforts on a particular aeroplane system. Prominent examples in the domain of propulsive system improvements feature propulsion electrification [33], advanced propulsive cycles [34], Boundary Layer Ingestion Propulsion [35], or simply - as has been the practice throughout the entire modern civil aviation era - new engines. An example of engine-level component-based improvement can be lean combustion technologies or a more efficient turbomachinery component. Analogously to the improvements seen at the whole aeroplane level, weight gains through improved structural materials can be sought with engine components, as exemplified prominently with composite engine fan blades researched for the next-generation Rolls-Royce *Trent1000* engines.

In the same vein as Fig.6 above, Fig.7 depicts a simplified causal network centering on the engine, as a constituent of a higher-level system that is the aeroplane. The engine designer will have a fine-grained description of the systems behaviour (thermodynamics, weight details, resulting total thrust). Engine behaviour/performance will be determined by upper-level parameters such as the free-stream conditions determined by the flight profile requirements defined at the whole-aeroplane level, as well as the maximum size admissible by the engine, here exemplified in a simple manner by the wing-to-ground clearance at the engine mounting location. A two-way multi-level causality is exemplified here by looking at a hypothetical case of fan component design, seen at its own local level from the respective designer's point of view. The local fan Model Variables are naturally determined by the input Data parameters this time coming either from the adjacent engine level (the pressure ratio to be respected), or from the aeroplane level, in form of the maximum

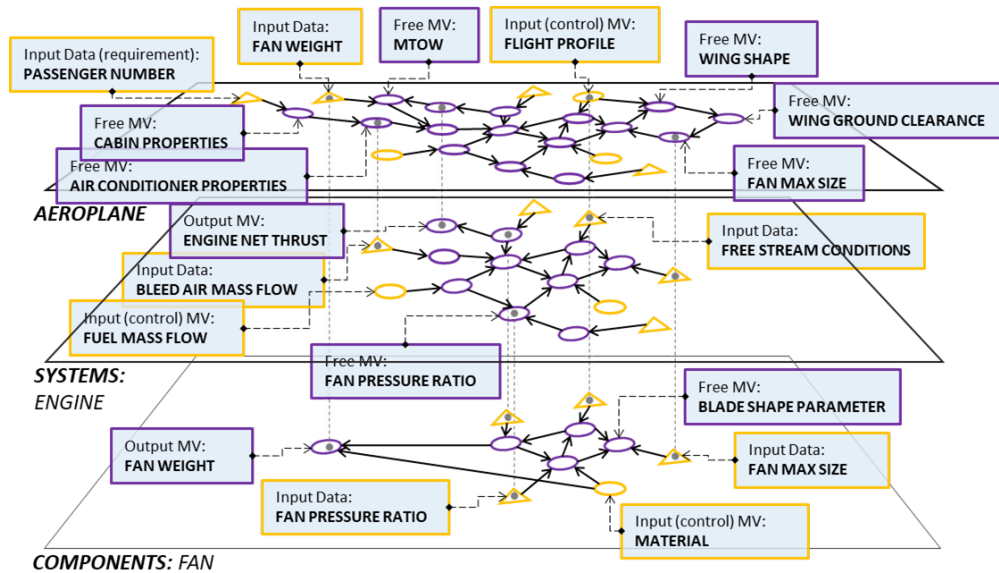


Fig. 7 Engine-level technology adaptation scenario illustrated from the causal network point of view: case of introduction of a composite fan component onto an existing engine.

size (diameter) that the fan can have. In turn, once the fan is fully designed under these constraints, it will result in a component weight, which will provide a Data-type parameter to the whole-aeroplane weight build-up calculations. While no fundamental new insight has been provided about the iterative nature of the aeroplane design, the contribution of causal networks is in providing a new vantage point that could help tackle potential inconsistencies between the various involved actors. This holds particularly true if radically new technologies are to be pursued, which are inherently characterised by potentially newly emergent complex behaviour whose management could be decisive in the success of the concept.

B. Operations/Air Traffic Management

Another prominently-featured type of strategy concerns the actors responsible for the traffic aspect of aviation. Innovative concepts in the domain of operations and traffic management include:

- Optimising aeroplane flight profiles to fly as closely as possible to the design conditions, rather than at conditions that act detrimentally on the aerodynamic or propulsive efficiency.
- A subset of the mission optimisation focusing on the on-ground segments: optimisation of ground operations to

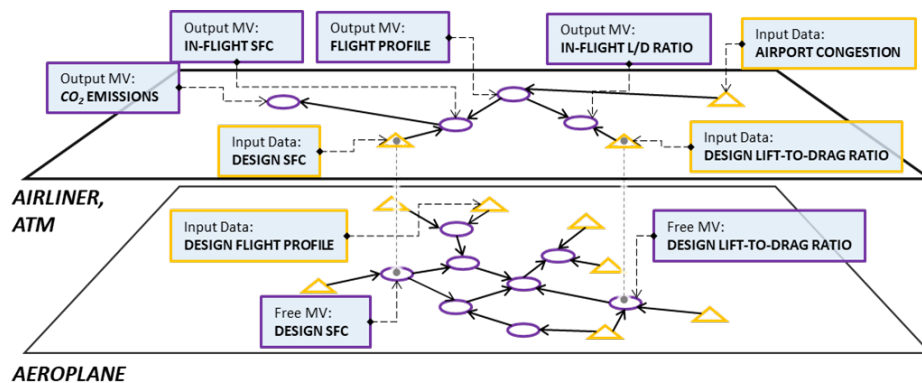


Fig. 8 Operation and ATM adaptation scenarios illustrated from the causal network point of view: case of air traffic management and a given aeroplane technology level influencing operator's fuel and emissions performance.

avoid excessive taxiing, or excessive/unnecessary loitering at airports that get crowded due to mismanagement or unforeseen circumstances.

- Flying several aeroplanes in formation flight, to benefit from collective aerodynamic efficiency in the same way that long-distance migrating birds do.

The causal network representing this point of view is illustrated in Fig.8. From the point of view of a hypothetical airliner who manages a fleet of a certain aeroplane type would take the aeroplane performance, airport capacities, or traffic scheduling in the neighbouring air-traffic systems as Data. In turn, its own Model Variables would include parameters describing operating cost models, crew availability or flight schedules.

C. Aviation Infrastructures External to the Aeroplane

Although not of prime importance, at least for what concerns the direct greenhouse gas emissions of the aviation sector, the enabling infrastructures category is an indispensable part of the long-term optimisation strategies for the industry. The scenarios on external structures in question concern for example, among others:

- Airports, with notably ground operations energy efficiency and/or type of energy source used for the operation as well as for energy provision to the aircraft while grounded.
- Manufacturing, where the optimisation objectives revolve around the industry's carbon footprint and overall ecological impact related to the used energy mix and material sourcing.

The causal network representing this point of view is illustrated in Fig.9. The scenario represents a situation where a production of a given energy source to be stored at the airport for provision during the turnover phase is represented as a Model Variable from the point of view of the energy sector, constrained by their own local Data. In combination with the airport-level constraint on the free space (Data), this results in some energy provision capacity to the aeroplane. For a fixed aeroplane technology (aeroplane local Data), for a hypothetical scenario of pressure by the airliners to maintain a certain turnover frequency (Data at the aeroplane level), the aeroplane designer could reach for higher power densities of e.g. propulsive system components (Model Variables), which could in turn into pressure on the manufacturers (Data), resulting in more polluting emissions at a given manufacturing technology level (Data).

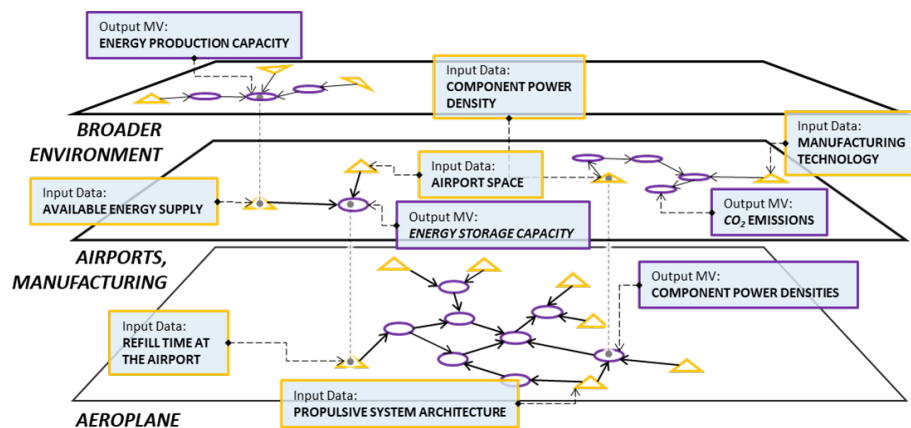


Fig. 9 Surrounding infrastructures adaptation scenarios illustrated from the causal network point of view: case of airport and aeroplane technology limitations influencing the manufacturing industry.

D. Energy Sources

The strategy featured prominently in contemporary research and development and extensively discussed in the public arena is the conceptually simple pathway of the kerosene replacement with energy carriers characterised by less/no in-operation production of undesirable chemical species, or the purported closed-carbon-loop feature labeled "net-zero". Such scenarios include:

- Hybridisation/electrification of the propulsion and/or the non-propulsive systems ("More Electric Aircraft" paradigm),
- Hydrogen,
- "Sustainable Aviation Fuels",

- Other energy carriers such as Liquid natural gas or Ammonia.

The causal network representing this point of view is illustrated in Fig.10. The illustration depicts a simple scenario of fixed aeroplane technology and operating cycles resulting in demand for synthesis of an alternative fuel (Model Variable from the point of view of the aeroplane designers and operators, Data from the point of view of the energy production sector). The demand, at a certain technology maturity level for the synthesis will have absorbed CO_2 , invested energy or arable land used as an outcome, represented as Model Variables.

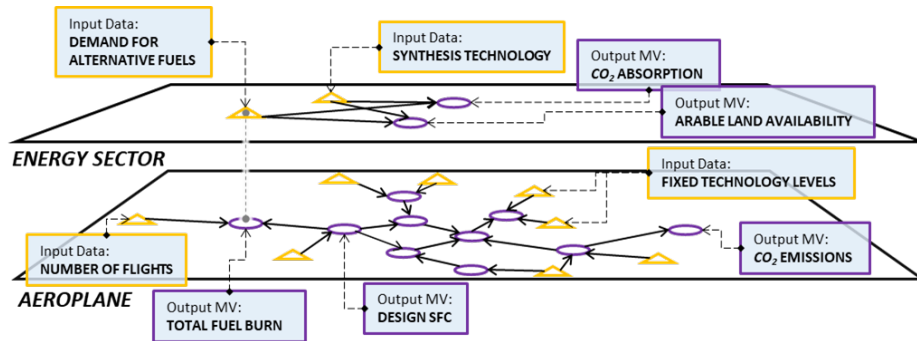


Fig. 10 Energy source-related adaptation scenario illustrated from the causal network point of view: case of demand for alternative fuels at fixed aeroplane technology level.

E. External measures

Finally, another prominent way to conceptually support the idea of current and future aviation climate neutrality scenarios are the measures external to the aviation industry, mainly driven by economic reasoning. Considering the classical economic concept of "externalities" where any outcome not included within a transaction is "external" to the parties performing the transaction, and thus not of their immediate concern - the idea behind market-based actions is to financially compensate the polluting effects. Various "carbon offsetting" and "carbon credits/trading" schemes have been debated and introduced, for example the ICAO "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)" scheme as ways to "compensate" the emissions of the industry elsewhere by investing the collected revenue into planting forests or carbon capture.

The causal network representing this point of view is illustrated in Fig.11. The depicted situation represents a situation of the industry practices and technology levels being at the state of the art level (Data parameters), such that they result in CO_2 emissions being represented by a Model Variable at their local level, as well as the amount of money they pay in carbon taxing or carbon offset/trading investments. At the separate level of the hypothetical sector dealing with the carbon offsets, the investments and the offset requirements translate into input Data, which result in certain CO_2 absorption, which together with the CO_2 existing and generated by the natural dynamics, and what has not been effectively absorbed, results in the total atmospheric CO_2 being represented as a model variable.

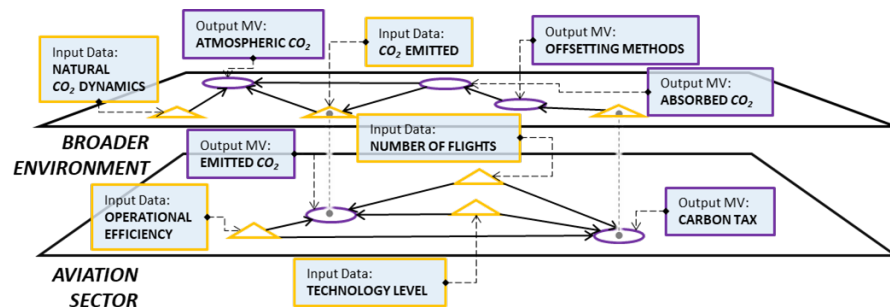


Fig. 11 External measure-related adaptation scenarios illustrated from the causal network point of view.

The reader is reminded that the presented scenarios serve as toy models of sort to illustrate the descriptive capabilities of the presented casual network framework; as such, their purpose is not to fully explain the tackled scenarios in their

full detail. Rather, the goal is to demonstrate that versatile systems at different scale can be represented on a unique simple common ground which incorporates idiosyncratic points of view of the involved actors.

VI. Common Currencies

A. Energy Flows

In the final chapter, the idea of system coarse-graining is correlated to a figure of merit of interest, without which no coherent quantitative comparison of various scenarios for the aviation and its individual constituents would be possible. In line with the historical tendency of the fuel flow being a double agent of optimisation by representing the operating cost through direct fuel burn and the environmental impact through the associated gaseous emissions, aeroplane operational energy is chosen as a figure of merit for this demonstration.

The paper assumes that a first-order qualitative analysis could capture the global fleet polluting impact if the total energy expenditure thereof could be captured. This postulate is somewhat akin to the work presented by Delbecq et al. in their modified version of the Kaya equation [11], as well as to the approach adopted by Jensen et al. in their discussion on US-based pathways towards 2050 climate neutrality [25]. As previously succinctly introduced in [36], a clear coarse-graining of the global fleet into a number of distinct categories indexed a can be assumed. The global energy expenditure can then be approximated as aggregate contributions all the constituent categories, expressed as follows:

$$\bar{E}_{global} \approx \sum_a \left(\bar{N} * \bar{E}_{op.cycle,DP} * \bar{\eta}_{op.} \right)_a \quad (1)$$

For the moment, the equation terms are not uncorrelated, which will be accounted for once a full representation of this system is formalised using the causal networks; this incompleteness does not influence the presented theoretical development. For each category a the terms within the parentheses are meant to represent, respectively:

- \bar{N} - mean flight frequency of an aeroplane of the given category,
- $\bar{E}_{op.cycle,DP}$ - mean operating cycle energy at the design point, i.e. design mission profile,
- $\bar{\eta}_{op.}$ - mean operating efficiency which deviates this design mission energy from the optimal value, basically accounting for the operational imperfections that are unavoidable in reality.

Looking at these parameters alone, some improvement strategies elaborated earlier are clearly identifiable. Before delving deeper into that aspect, it might be instructive to coarse-grain the operating energy term somewhat further. A theoretical lower limit to the aeroplane energy expenditure $E_{op.cycle,theoretical}$ can be postulated (as theorised by e.g. McMasters and Cummings [37]), which is offset by the inefficiency η_{system} of the aeroplane system architecture:

$$E_{op.cycle,DP} \propto (E_{op.cycle,theoretical}, \eta_{system}) \quad (2)$$

$$E_{op.cycle,theoretical} = f(\text{missionrequirements}) \quad (3)$$

$$\eta_{system} = f(\text{architecture}, \text{componentproperties}) \quad (4)$$

It is now a matter of routine to present the above relations in the causal network framework seen from the point of view of a hypothetical agent who book-keeps the global energy performance, with no relevant insight into things like airline operations or aeroplane design and development. (Fig.12) In the first place, the system can be represented in the default causality scenario, i.e. with all the causal flows are as they would be in reality:

- An assumed global fleet, operated at a certain frequency N dictated by the airliner objectives under the ATM, airport, political, etc. constraints,
- And operating aeroplanes of certain characteristics represented by the $E_{op.cycle}$, managed by the aeroplane OEM's,
- Would result in the respective energy consumption which can be aggregated to a total, fleet-level figure.

It means that the example treats energy, as well as all its coarse-grained constituents (the fleet-contributions and the underlying operating and technological characteristics) as an output Model Variable, with the upstream factors that determine them are strictly input; the actor estimating the energy expenditure is oblivious to factors determining the state of these inputs. This scenario represents what happens if one simply assumes each upstream characteristic to be a given,

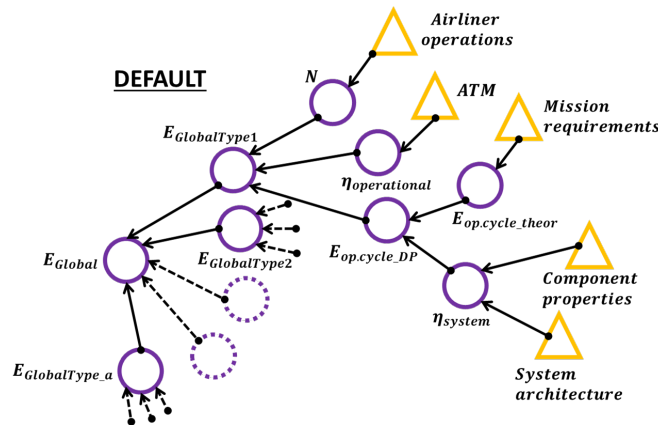


Fig. 12 Global fleet energy theoretical breakdown (Eqs. 1-4) represented as a causal network.

and goes on to attain the respective individual objectives without knowing what the aggregate performance (energy expenditure in this case) would be. As seen in the introductory summary in Fig.13, the causal network formalism allows formulating inversion of the default scenarios in various ways, the only condition being that the overall consistency of the network be satisfied. In this particular example, two of numerous possible scenarios are illustrated in Fig.13, both of which take it as a starting point that the global operating energy E_{global} parameter input state is reversed, to allow its value to be imposed from top-down, which will in turn propagate to the lower-level contributions $E_{globalType_a}$, and further to their respective upstream causal predecessors. The two simple scenarios in the figure present a hypothetical case where the technology levels and global operations are kept unperturbed, and any top level global energy constraint will act only on the number of operated flights. ("Inverted 1" illustration) Using the same logic, the second illustration acts on aeroplane system architecture (technology level) with the other contributions remaining free ("Inverted 2" illustration).

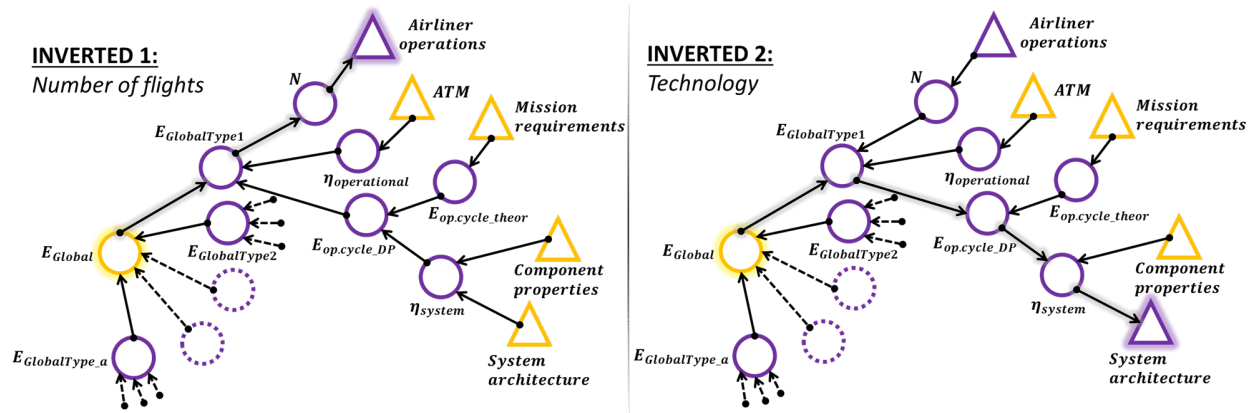


Fig. 13 The same global fleet energy causal graph, under two simple inverse-causality scenarios: using total global energy as input and calculating the average flight frequency of the fleet type 1 (left); the same scenario, with the average fleet 1 system architecture design being calculated in turn.

In the example derived from simple correlations from Eqs.1-4 only energy expenditure is book-kept, for the purposes of demonstration. No explicit information is represented considering the means of energy production/storage for instance, or any impact on other socio-natural systems surrounding the aeroplane. Supposing that there is basic transparency in what the emissions trade factors and supply capabilities are - the only fundamental need for devising coherent scenarios in this energy-based framework would be an exact decomposition (coarse-graining) of the industry into consistent "book-keeping" categories, which communicate with each other as described above, without overlapping or leaving gaps. This is particularly emphasised because when undertaking global, high-level analyses - precision is often exchanged for width of scope due to limitations of computational power and/or time.

Remembering that the major high-level objective that motivates the work of this paper is exploration of scenarios to reconcile high-level objectives of the industry's natural environment and the industry socio-economic performance, the above example can be somewhat generalised to provide for a comprehensive common ground upon which the consistency of such scenarios could be evaluated. In the system presented in Figs.12 and 13 it is implicitly assumed that the represented situation represents an instantaneous (i.e. steady) state; there is no temporal component involved. The industry performance with respect to both the high-level objectives, but particularly when it comes to the natural environment impact, is a time-variable phenomenon, which is why the parameters from the above network should be represented accordingly. Moreover, the material grounds upon which the global objectives at hand depend are not only founded on energy consumption, but also on the consumption (and subsequent rejection) of various matter species, which should just as well be coherently book-kept. For that reason, to complete the picture derived so far, it is argued in the following that a meaningful representation of the system in global development scenarios should not be a system of fixed characteristics, but a system represented over a time frame of interest. That time frame is the system's life cycle.

B. Life Cycle: Matter, Energy and Information Flows

At this level, when impacts on high-level phenomena are evaluated from the point of view of interaction of various systems and the actors governing them, it becomes a matter of pedantry to distinguish between the engine and the whole aeroplane. Therefore, the following explanations will concern the whole aeroplane for conceptual simplicity, but it is underlined that the reasoning and the conclusions that follow are exactly the same from the point of view of the engine, or any other system.

It is argued that the minimal meaningful way to evaluate environmental impact of an industrial system is to have a clear idea of how the system modifies the flows of matter and energy in the surroundings that consist of other societal systems and the non-human natural world. A first-order approach to this is proposed hereby, for comprehensive conceptual and analytical understanding of the system of interest. In particular, it is argued that in the enunciated context, a rigorous life-cycle-based description is the one which enables book-keeping of everything that goes into the system and that the system rejects, namely:

- **Matter:** different matter species that are consumed by the system (e.g. manufacturing materials, energy carriers) or rejected by it (e.g. gaseous emissions, manufacturing and operational waste);
- **Energy:** the energy drawn by the system at different life cycle phases, for manufacturing, for maintenance, for ground operation, or produced/rejected by the system, often manifested in heat dissipation;
- **Information:** a more subtle feature of the presented abstract framework which will be explained further down in

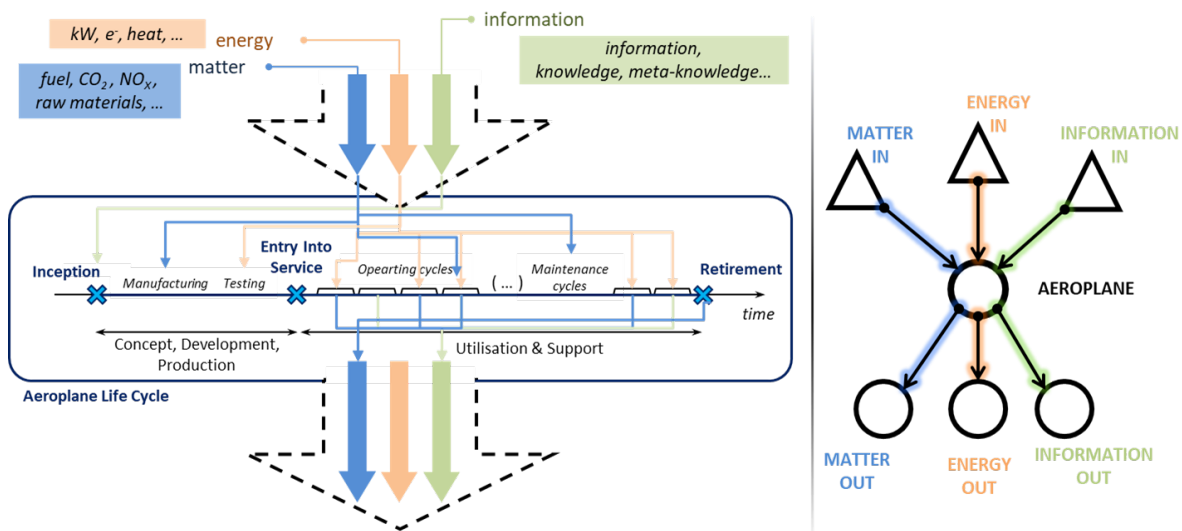


Fig. 14 Illustration of an aeroplane represented as the entirety of the life cycle, encompassing different phases between the inception and the retirement. (left) Analogously, this formalism is applicable to any system of interest at any coarse-graining level, which can be put in causal relationship with the other surrounding systems by virtue of parameter exchange. (right)

the text.

It now becomes conceptually very simple to investigate the engine and the aeroplane through the causal network prism, with the default description scenario saying:

- Data-type parameters representing primarily the matter and energy possible to divert toward the observed system,
- Control and free Model Variables representing the free design variables of the system,
- Output free Model Variables representing what comes out of the system, i.e. its operational and economic performance for the different actors, pollution, etc.

The life-cycle time interval is defined according to the principles presented by Brazier et al. [38], where the industrial system life phases span between the inception of the system and its final retirement, including the comprehensive phases prior to the entry into service (design, development, production), and the subsequent utilisation and support. The schematic representation of so-defined life cycle is presented on the left-hand side of Fig.14.

The right-hand side of Fig.14 represents the same aeroplane life-cycle using the causal network formalism. In the simplified - that is, very high-level, coarsely-grained - representation, the aeroplane object is an object in time which draws from the systems it does not have insight into (matter and energy sources) and downstream it rejects matter and energy as an outcome of its own features and operational scenarios. For illustration, and to emphasise the position of the aeroplane engine, an equivalent, more finely-grained illustration is provided in Fig.15 It is pointed out at this moment that in addition to providing a possibility for unambiguous interfacing of the system with its surroundings, the coarse-grained life-cycle representation also allows accounting for involvement of different stakeholders with different needs and desires for the same system, as well as the different points of view and the knowledge thereof.

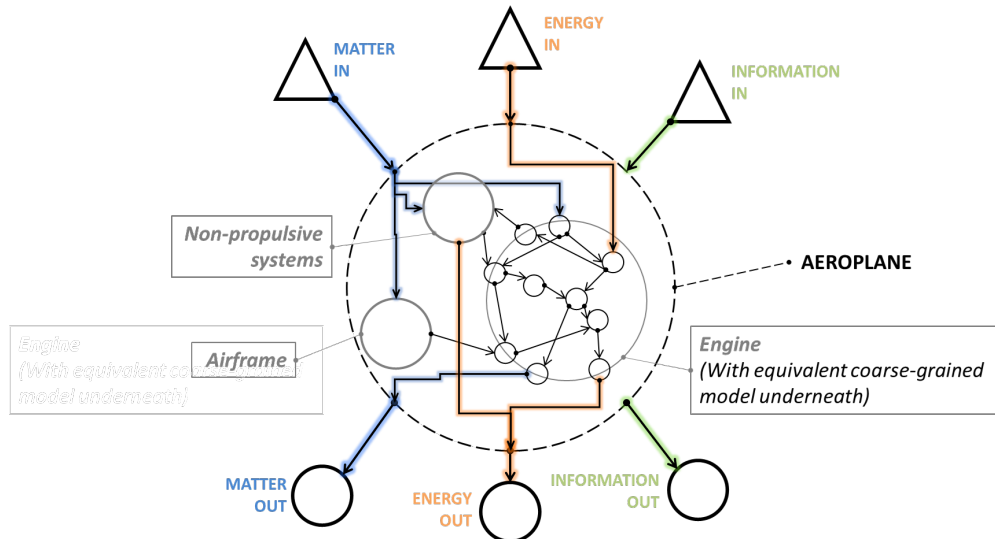


Fig. 15 More finely-grained depiction of a causal network (eq. to the one in Fig.14) depicting the aeroplane as object which exchanges matter, energy and information with its environment over the entirety of its life cycle.

In elaboration of the simple high-level performance model from the previous section, the operating energy alone was considered, whereas the aeroplane-related energy expenditure is also directly correlated with the energy expenditure during the design, manufacturing, testing, certification, maintenance and other non-operational activities; the same is true of the flows of matter in and out of the system. In addition to being able to account for these within the system boundaries, this formalism enables more transparency and consistency regarding the upstream dependencies. For example, when discussing optimisation scenarios based on the measures that are strictly speaking external to the system, e.g. the prominent reliance on "sustainable aviation fuels" or other alternative energy sources/carriers, employing the different causal scenarios (default or inverse) can help determine the consistency of proposed scenarios. For instance, in an unconstrained scenario where aeroplane technology and operational developments assume positive developments under the hypothesis of there being enough alternative energy carriers that do no harm to the natural environment, the hypothesis can be tested simply by appending the aeroplane life-cycle model to a model describing e.g. the available energy production capabilities and the natural matter and energy flows, by imposing the consistent causal scenario, and ascertaining whether the elaborated scenario is meaningful or not. That way, for example, in order to ascertain whether

the "sustainable aviation fuels" are viable solution to the aeroplane optimisation problem, it is possible to represent them as matter-type input to the system rather than a quantity of energy without label. That way, it could be exchanged upstream against the impacts its production might have on the adjacent systems such as the agricultural industry, or the natural systems represented by nitrate and phosphorus cycles. The same goes for the matter influx for the manufacturing processes (e.g. rare metals for electronics, whose extraction is a major polluter), which again concerns life cycle phases of the aeroplane that have no direct link to the operation. The presented reasoning is inspired by and in line with the principles of industrial ecology [39], a relatively recent discipline which endeavours to optimise the industrial presence in the natural world by careful estimation of the matter species the industries exchange with the environments they are embedded in. Furthermore, influence of works of Odum [40] who worked on energy flows in natural ecosystems, and Paynter [41] who introduced industrial system modelling by virtue of energy/power networks and bond graphs is also recognised.

Finally, the *information* life-cycle parameter that is included in the description is a subtle, but indispensable feature to include accounting for the knowledge of the external environment that the system can reliably use in order to tune its own behaviour and outputs. Information "IN" parameters regroup what the actor needs to know about the surroundings, including the ontology of the given surrounding system and its state. Information "OUT" is the same type of knowledge that is rendered transparent by the actor to their surroundings.

C. The Structure of Civil Aviation (R)Evolution(s)

Depending on the input-output state the system Data and Model Variables assume (cf. Fig.5), two principle ways to articulate the models and derive scenarios from them can be articulated:

- 1) **Descriptive:** where the system model follows the default causal scenario, as if the systems were merely observed and evaluated. (see the example in Fig.12) This means assuming the relevant Data parameter values (or receiving them from the associated actor in possession of the information), running the model for the range of control Model Variable values of interest (if any), and calculating the resulting output given by the free Model Variables. This scenario could arguably also be referred to as *Bottom-Up*, as it calculates higher-level performance from the aggregate lower-level inputs which all act freely.
- 2) **Prescriptive (normative):** where the free (output) Model Variables are constrained in order to impose a desired state, and in turn determine the Data and/or control Model Variables values. (Fig.13)) In accordance with the previous category, this scenario could be referred to as *Top-Down*.

Any of the above examples (Figs.6-11) where different system illustrations were made with their respective Data and Model Variables could be used to illustrate practical importance of the above two types of scenarios. At the whole aeroplane level, an example illustration can be the historical development of design for noise, which until the rise of strict community norms and noise compliance norms was arguably treated in the descriptive way. The parameters correlated to the emitted noise such as geometric shapes or air flow speeds would be designed according to objectives of aerodynamic performance, propulsive power or structural integrity. In turn, free Model Variable parameters describing the noise would come out as a result. With the emergence of noise compliance norms, a prescriptive scenario for the noise needed to be elaborated, and now the noise parameters (or the noise constraints) would assume input state, and the correlated aerodynamic, geometric and other parameters would have to adapt to those as well.

Higher up, at the fleet or industry level, the cumulative greenhouse gas emissions are direct outcome (free Model Variable in default scenario) of various features of aeroplane technologies and their operation, analogous to the global energy presented in the previous sections. In a descriptive scenario, the industry-level Data would be the passenger demand, macroeconomic/monetary considerations, national traffic policies, while control Model Variables could be the number of flights, number of aeroplanes built, the means/effort invested into evolving the technological capabilities, etc. The resulting Model Variables including all aspects of the industry performance, including the aforementioned environmental impact. This scenario represents what is commonly dubbed the "business as usual" model. A prescriptive scenario defined by inversion of some causality directions would in turn see a limit on environmental impacts with the rest of the Model Variables determined accordingly. (refer back to Fig.13)

While this might be an overly tedious way to describe what is arguably the common knowledge of correlations between parameters of a model and constrained versus unconstrained optimisation scenarios, the argumentation adds value because it allows introduction of governing actors into the discussion, and show how information exchange between these can lead to the proverbial missing of the global optimum where every actor seeks their own local optimum. Fig.16 emphasises the relevance of information exchange: 1) Hypothetical high-level complete overview of a system of interest is assumed; 2) The system is then separated among two adjacent actors; 3) The point of view of Actor 1

shows their own upstream dependencies, boundary, and the Model Variables whose outcome influence Actor 2; 4) The equivalent situation seen from the point of view of Actor 2, whose upstream dependencies include the outcome of Actor 1's actions; 5) Composite view of the two Actors' situation, accessible to a hypothetical high-level observer (e.g. to a full-system designer); 6) A conflicting/contradictory situation arising from isolated developments of the two systems.

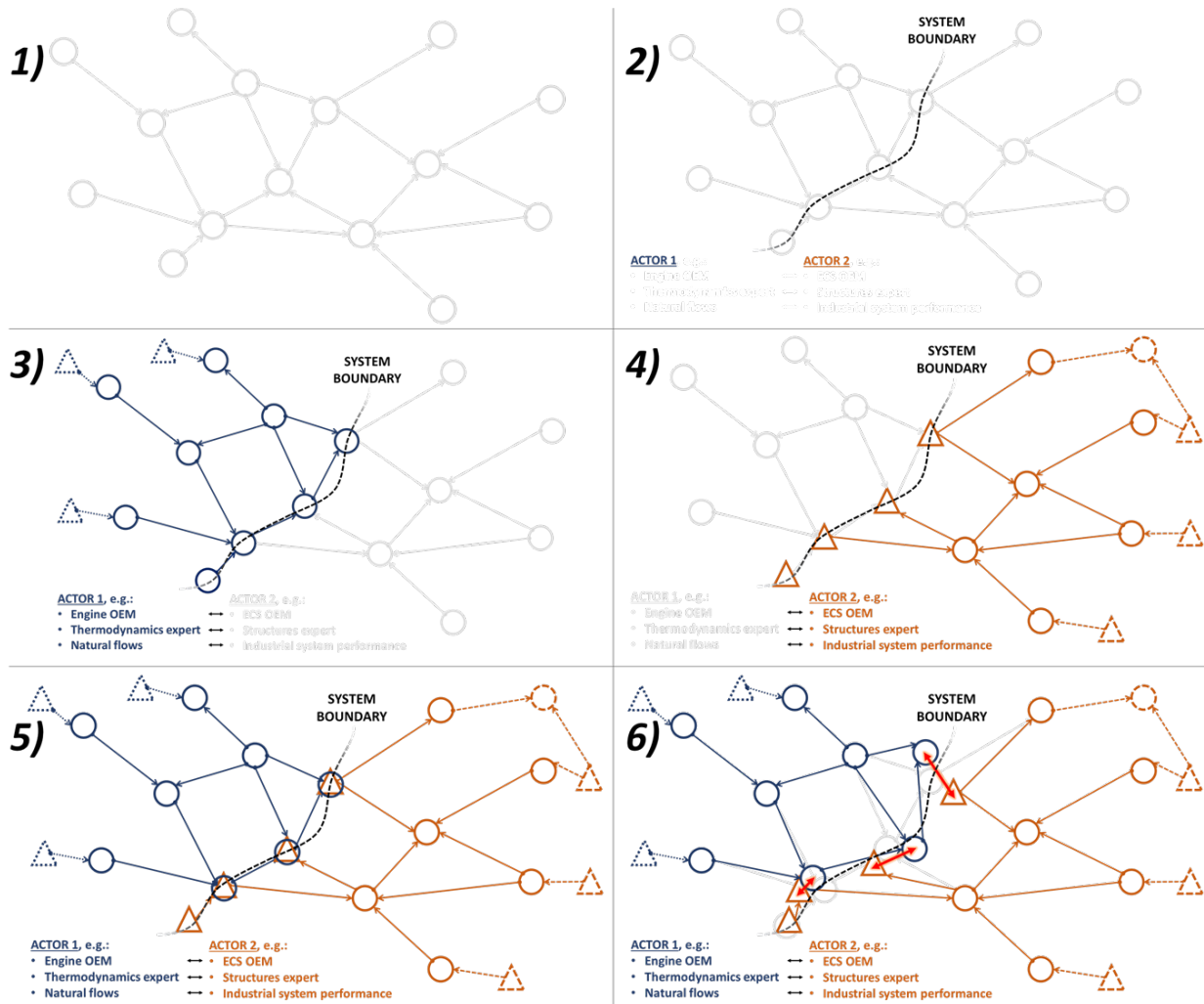


Fig. 16 Causal network principles employed to illustrate contradictory situations arising when adjacent systems pursue their respective developments in isolation.

The previous examples are not meant to advocate either for prescriptive or descriptive scenarios for either the engine, the aeroplane, the whole industry, or any other system involved. Careful readers will have noticed how easily any of these systems correlate to an immensely broader scope commonly outside of the domain of preliminary design modelling of the propulsive system of interest, with links to the matters of policy, politics, economy and numerous other everyday aspects of the complex global aviation system. The examples are rather meant to be seen as a single piece in the puzzle presented throughout the entire paper, where all the pieces work to create a conceptually simple framework consisting of:

- Coarse-graining: Breaking down any system into a manageable number of elements with clearly identified mutual correlations;
- Causal network, Data, Model-Variable parameters: defining the basic categorisation for the coarse-grained elements/parameters and assigning meaning to the causal relationships they could assume;
- Emphasising that Data type parameters represent the limits of knowledge of the given system;
- Recursive nature of coarse-graining and the causal links: the limit of knowledge can in principle be overcome

- conceptually by replacing Data with broader models/increasing the coarse-graining;
- Life cycle: conceptualising the system as the time integral of its entire existence;
- Matter/Energy/Information exchanges: if the system is to be compatible with the natural flow dynamics, i.e. sustainable.

The argument of the paper is that this can lead to local optimisations and scenario development for the multitude of actors with clear and consistent book-keeping of the individual contributions to the global optimisation at hand. With clear idea of the high-level figures of merit which concern all the involved stakeholders and phenomena of interest, with full understanding of prescriptive/descriptive scenarios, with well-managed system boundaries and the information exchange between them - global optimisation scenarios could be proposed and evaluated at any relevant coarse-graining level. Arguably with such approach, it be would possible to confidently know which scenario works on the whole, and for which of the involved actors.

VII. Summary and Ongoing Developments

The paper presents presents a simplified global overview of the multi-faceted optimisation of various constituent elements of the civil aeronautical industry. The identified high-level problem is in attempts to resolve the non-linear industry-level problem of compatibility between growth imperatives and environmental impact of the constituent actors who separately pursue of their individual goals. To elucidate the situation, a summary of representative and relevant scenarios for long-term industry evolution was presented. The focus of this paper being the propulsive system, the summary focused on the way the scenarios perceive this system, as well as its interface with complex environment it is embedded in.

On that basis, to contribute to gaining deeper understanding of potential inconsistencies observed in such scenarios- the paper proposes a simple explanatory framework to capture the behaviour of different systems and the actors involved in their governance. The framework is based on the idea of coarse-graining, and on subsequent derivation of causal networks. The classification of parameters that constitute the network ('Data' and 'Model Variable') and their mutual causal relationships ('default/descriptive' or 'inverted/prescriptive') under different scenarios, help the designer define the boundary between the system and the complex environment, which opens the doors to deeper understanding of its

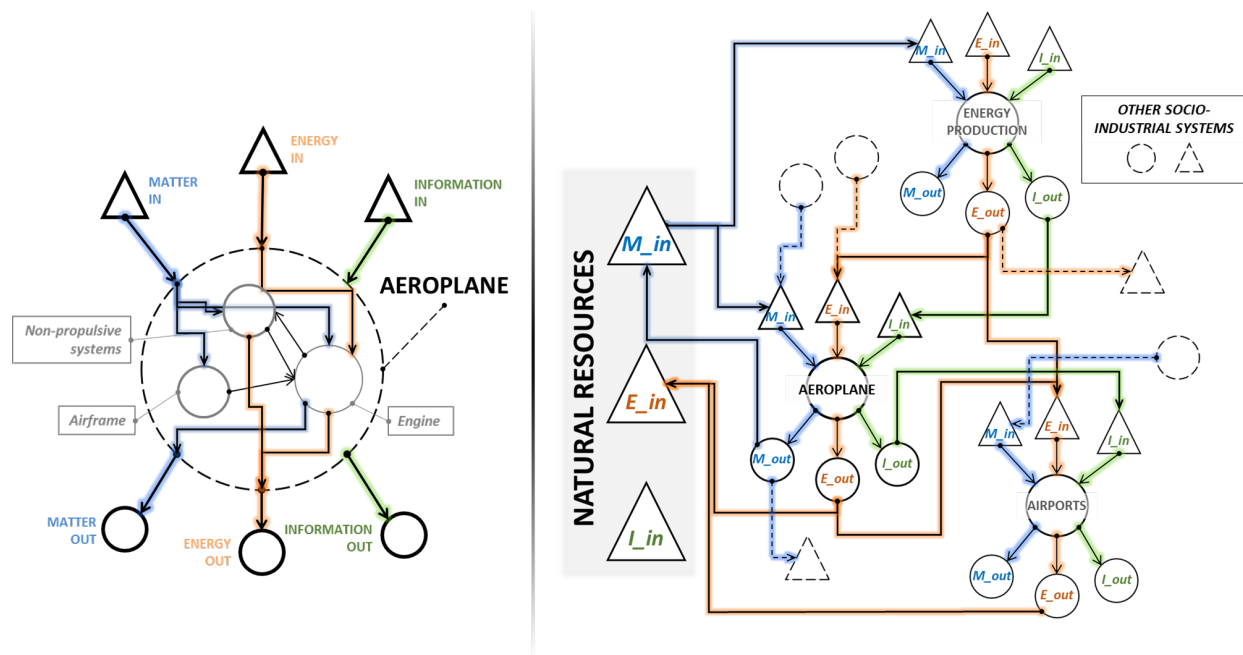


Fig. 17 Conceptualising the problem of sustainability on the basis of life-cycle representation of objects from Fig.15 and the flux of matter, energy and information (left): necessity to clearly delineate all the systems, represented as entire life cycles feeding on each other and working within the constraints imposed by the non-human natural environment (right).

position within a higher-level emergent system. This includes the impact it might have on the broader environment, but also the potential negative feedback loops. The coarse-graining formalism works recursively, in principle allowing to represent and analyse consistency of any system involved in the aeronautical industry.

By framing the system as a complete life cycle between the earliest inception and the end of life, combined with the coarse-grained network hypotheses, it becomes conceptually simple to describe the sustainability problem. Each system, for the duration of its life, exchanges with everything else and with the rest of the natural world alike. (Fig.17) It can be presented equivalently as a causal network, in which everything is mutually entangled, evolving in unison. A framework like this might make it easier to pinpoint the weaknesses in knowledge and intuitions of actors at all levels, and to get everybody to coordinate more productively in pursuit of the common goals.

Future works on the framework include extending it to represent time-dependent situations. Furthermore, inclusion of stakeholders and their coordination, directly linked with modelling of information flows through the causal networks will follow, arguably closing the circle in terms of desired representativity of one such modelling framework.

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