Chapter

Electrification for Aero-Engines: A Case Study of Modularization in New Product Development

Edgar Jeevan Danaraj

Abstract

Modularization of hybrid-electric propulsion for commercial aircraft is becoming a reality in air transportation. The main intent of an electric architecture is to produce less carbon emissions and advance towards sustainability in the aeronautics industry. Due to regulatory and customer requirements for new technologies aimed at climate change and pollution, the integration of hybrid electric engine design become more challenging. Conceptual modular and integral product architectures are being compared with conventional and new constructions. A Design Structure Matrix (DSM) model is developed to analyze configuration of sub-component and their relationships through interaction between system elements. The DSM model includes product decomposition and cyclic task interdependencies to understand the extent of modularity in the product life cycle. The traditional turbofan engine architecture will be compared with hybrid electric propulsion engine architecture. The analysis indicates that the electric engine configuration constitutes a shift to a more distributed and less modular architecture. The DSM model reported a 19% increase in density of connectivity between components and 58% decrease in terms of structural complexity. The significance of these changes demonstrates that the more distributed architecture of the fully electric engine architecture requires less effort in system integration than the geared traditional turbofan architecture.

Keywords: aircraft, aerospace, engines, electrification, sustainability

1. Introduction

The architecture for new and future generation aircraft engines is on the horizon. Building the architecture of a new product is a key design task that affects the steps of product development lifecycle. According to Ulrich, product architecture is the scheme by which the functional components of a product are allocated to physical units [1]. This definition has been widely accepted by many organizations. Comfort, safety, seating capacity, reliability and speed are important factors in today's world of urban air mobility electrification. Rapid technological advancement requires rapid research into stronger lightweight materials and higher battery densities to innovate and grow the product architecture to the next level and embrace the future of commercial flight.

The design of an aircraft engine has been relatively similar for decades, utilizing gas turbine fundamentals since the early twentieth century. Hybrid-electric technology is a crucial means of establishing new standards for aviation sustainability in a variety of applications by maximizing the propulsion system's efficiency. Building blocks of the design structure matrix (DSM) for hybrid-electric engines will be created to compare the architectures between gas turbine and hybrid-electric engines. At the end of the chapter, the matrix will map out and outline product change during technology insertion and solve the question on how a modular architecture could make standardization possible.

2. Gas turbine engines

The typical aero-engine is designed in sectional-modular architecture type that can be assembled and disassembled, or even interchanged with modules from another compatible engine, without the need for specific retesting or balancing. This unique advantage supports production maintenance and reduces process downtime for the operator. The target to reduce emissions caused by conventional gas turbine engines in realization of the growing air transport demand drives research for new product architectures.

Previous work lacks the understanding on how interactions between components behave in varying modular platforms. Hence, it is important to know the dependency of each individual component (dependent, parallel, or coupled) in relation to the coordinated activities in the development lifecycle. **Figures 1-5** shows various gas turbine engine configurations and interconnected components.

3. Hybrid and electric engines

Hybrid aircraft engines will combine the advantages of a turbine engine, like the high energy density of jet fuel, over those of an electric engine, like lower noise levels and less upkeep. Existing battery powered electric propulsion systems in light UAVs and quadcopters provide environmentally friendly concepts with significantly reduced carbon footprint. Air traffic management, adverse weather conditions and battery capacity required for long range travel, energy-to-weight ratio and cooling efficiency are some constraints often debated during technological development of hybrid design concepts.

Figure 1.
Modular engine components in a typical engine architecture [2].

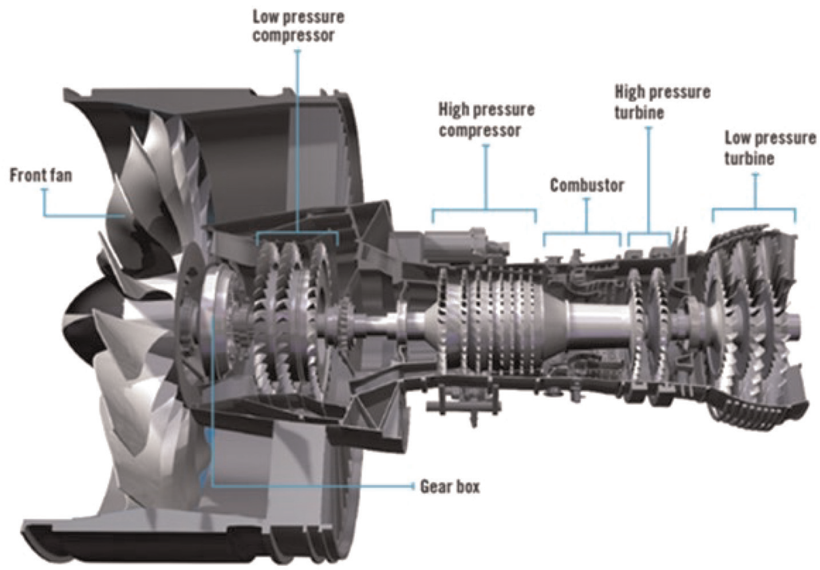

Figure 2.
Pratt and Whitney geared turbofan [3].

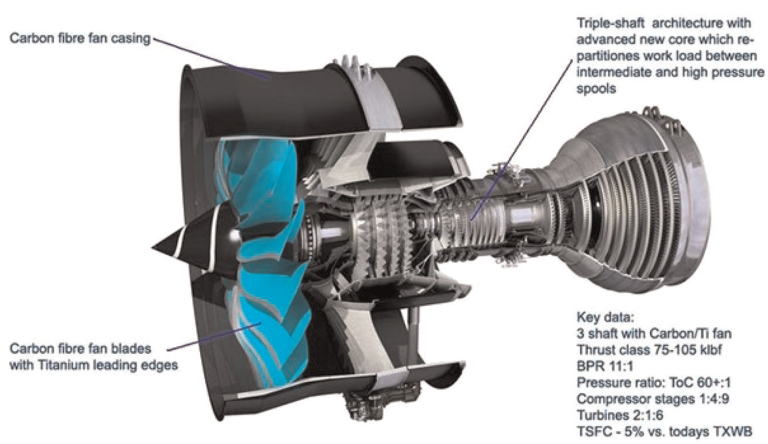

Figure 3.
Rolls-Royce ultrafan engine [4].

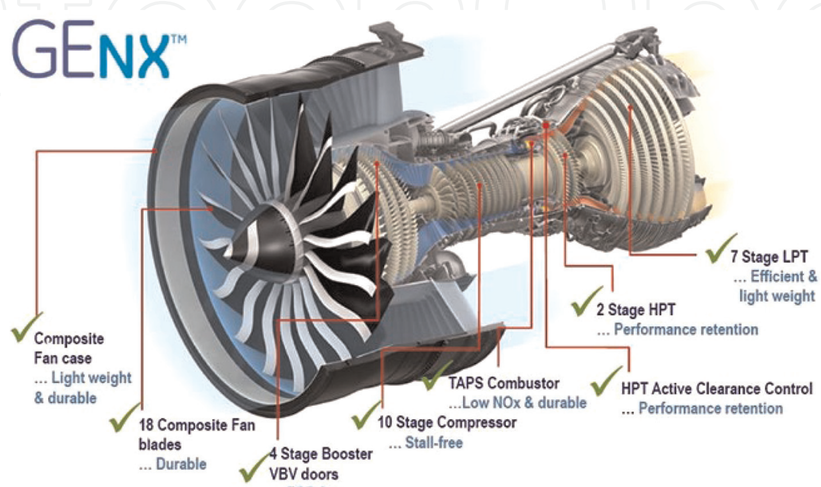

Figure 4.
General electric NX engine [5].

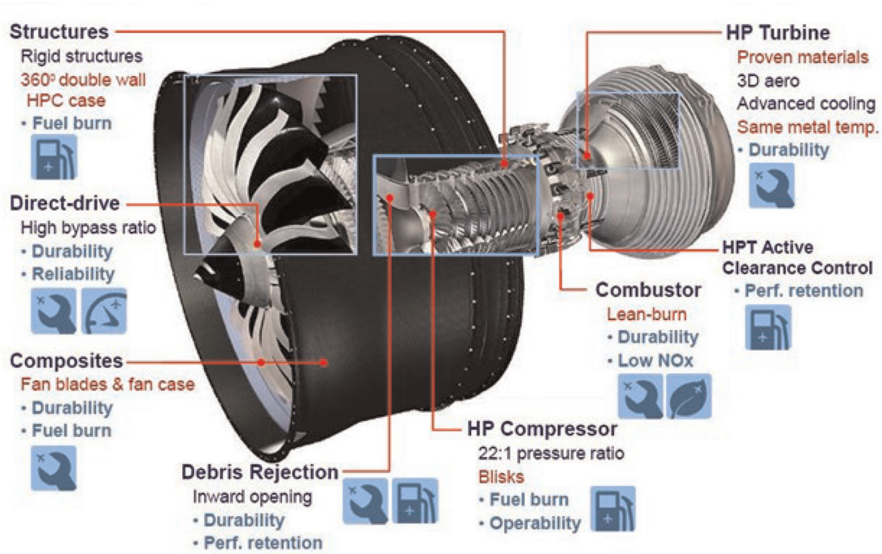

Figure 5.
CFM leap engine [6].

Gas turbine engines have mechanically turned rotors, propellers, or fans with fuel-burning engines. However, a distributed electric propulsion architecture, in which several electric motors can be tilted or turned off for both vertical take-off and horizontal flight, is used in a lot of recent designs. Anywhere on an aircraft, a turbo-generator can supply electric power to multiple electric motors.

3.1 Boeing and Aurora

The all-electric autonomous passenger air vehicle Aurora Flight Sciences, a subsidiary of aerospace giant Boeing, flew for the first time in a test flight. The prototype, according to Boeing, is powered by an electric propulsion system and designed for fully autonomous flight from take-off to landing, with a range of up to 50 miles. Its airframe coordinating the drive and wing frameworks to realize proficient lift and forward flight. Boeing's futuristic NeXt division, which also oversees its heavy-duty drone prototype that can lift a 500-pound payload, carried out the test. Aurora Flight Sciences have collaborated with Uber to create a arrange of "flying taxis" that work on "Uber Air" item, which it plans to dispatch in 2023.

3.2 Airbus, Rolls-Royce, and Siemens

In 2017, a 100-seat regional jet with a hybrid electric drive for a turbine was developed by Siemens, Airbus, and Rolls Royce. The E-Fan X hybrid-electric innovation demonstrator was temporarily flown on a BAe 146 flying testbed, with one of the aircraft's four gas turbine motors supplanted by a 2-megawatt electric engine. Arrangements were made to replace a second gas turbine with an electric engine once framework development had been demonstrated.

The compact 2.5 MW (3400 hp) generator was run in 2019 and first flight was scheduled for 2021. The AE2100 turboprop was from a Saab 2000 feeding the battery pack and a Siemens SP2000 electric motor (with a 10 kW/kg power-to-weight ratio) replacing one Honeywell LF507 engine with a Rolls-Royce AE 3007 fan through a 3000 volts AC/DC distribution. However, the program was canceled in 2020 due to the COVID-19 pandemic.

3.3 Rolls-Royce

Distributed propulsion, in which a single turbine turns multiple propellers on an aircraft, is made possible by hybridization. Rolls-Royce and APUS, a company that specializes in aviation engineering, and the Brandenburg University of Technology (BTU) are creating a hybrid-electric flight demonstration aircraft. The M250, the engine of choice for hybridization served as the foundation for the eVTOL concept developed by Rolls-Royce. The M250 can power a four- to five-passenger vehicle that can travel at 250 mph over a range of at least 500 miles by adding an electrical generator to the system. The gas turbine produces electricity between 300 and 400 kW, and a battery system can supply an additional 300 to 400 KW for hovering. The aircraft can also perform a standard take-off and landing. All-electric VTOLs for short-range missions will emerge in the longer term as battery technology advances, but hybrids will likely continue to serve longer-range missions (**Figure 6**).

3.4 General electric and XTI

GE Aviation's business and general aviation unit's leader in hybrid-electric pursuits. The TriFan 600 will be powered by a new hybrid-electric propulsion system developed by GE Aviation and XTI Aircraft Company. This contrasts with conventional turboprop engines, which require a distinct turbine for each propeller. It makes it possible for a greater number of hybrid aircraft to utilize a greater number of propulsion sources, allowing aircraft designers to re-evaluate even the most fundamental aspects of aircraft design. The current battery technology does not allow for sufficient energy density to make a long-distance electric aircraft feasible.

The TriFan 600's Catalyst will enable it to travel at a much higher altitude (30,000 feet) and at a faster rate than any electric aircraft currently on the market. The Catalyst's power will also make it possible to transport a much larger

Figure 6.
Rolls-Royce M50 engine for the APUS i-5 plane [7].

Figure 7.
General electric and XTI TriFan 600 [8].

payload while still being able to take-off and land vertically. GE engineers have been able to reduce the typical 800 components that would have been made using conventional methods down to just a dozen or so printed parts using 3D printing. They were able to use less fuel and reduce the Catalyst's weight by 5% with this strategy. The TriFan's engine will have approximately 1400 horsepower, or 1 megawatt of power (**Figure 7**).

3.5 Honeywell

Honeywell's hybrid-electric propulsion includes a turbogenerator that produces 400 kilowatts by combining two miniaturized generators with the robust, flight-tested HTS900 engine. The turbogenerator system can supply motors or high-capacity batteries with conventional or bio-derived jet fuel. In addition, Honeywell introduced the first 1 MW generator for the aerospace industry, which had the same power density as our 200 kVA generator. The 1 MW generator has a weight of 280 lb. The HGT1700 auxiliary power unit, which is currently used on every Airbus A350 XWB, will be combined with this generator to create a turbogenerator that is 2.5 times more powerful than the version that the company unveiled in 2019 (**Figure 8**).

3.6 Collins aerospace and Pratt & Whitney Canada

A P&WC engine and a Collins electric motor of 1 megawatt will be combined in a parallel hybrid configuration with a 50/50 power split on one side of an experimental De Havilland Dash 8–100 aircraft. The motor by Collins has a high-power density and efficiency. The program is aiming for a 30% increase in fuel efficiency and correspondingly lower CO2 emissions. The fuel-burning engine will be able to be optimized

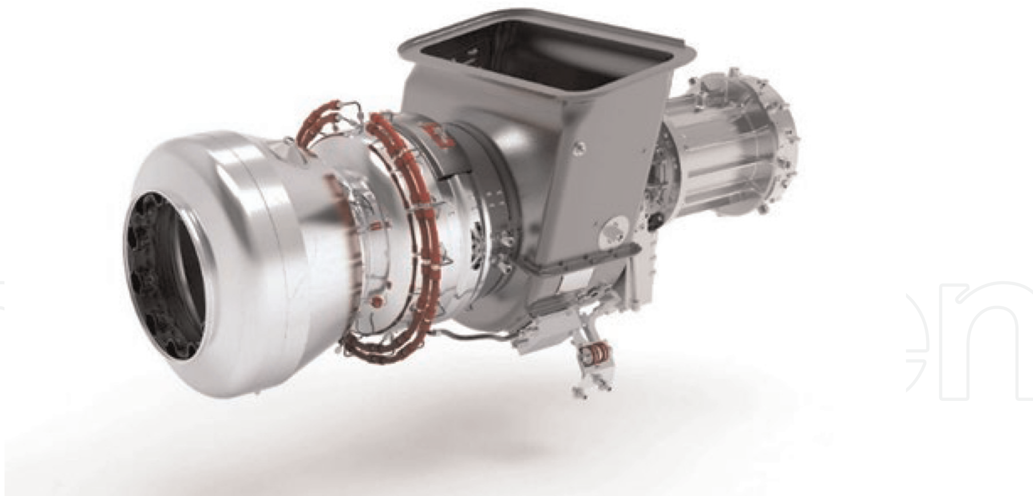

Figure 8.
Honeywell 1-megawatt turbogenerator [9].

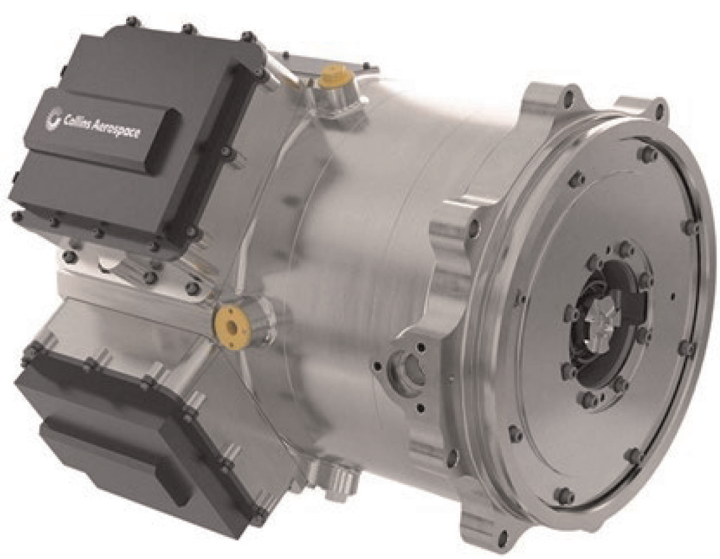

Figure 9.
Collins aerospace 1-Megawatt electric motor [10].

for cruise efficiency because the electric motor will provide additional power during take-off and climb. Additionally, the new technology will be constructed to operate entirely on Sustainable Aviation Fuel (SAF) (**Figure 9**).

3.7 Lilium

Ducted Electric Vectored Thrust (DEVT) is a proprietary technology from Lilium Jet, which incorporates electric jet engines into the wing flaps for thrust vectoring. This provides advantages in payload, aerodynamic efficiency, and a lower noise profile. Each of the 36 individually controllable flaps in the propulsion system has a ducted electric fan and serves as a lifting and control surface. On the canard and main wing, the 36 ducted fans are embedded in a 1:2 ratio. The ducted fans are incorporated into the wings, reducing weight, and minimizing aerodynamic drag loss by eliminating the need for separate nacelles.

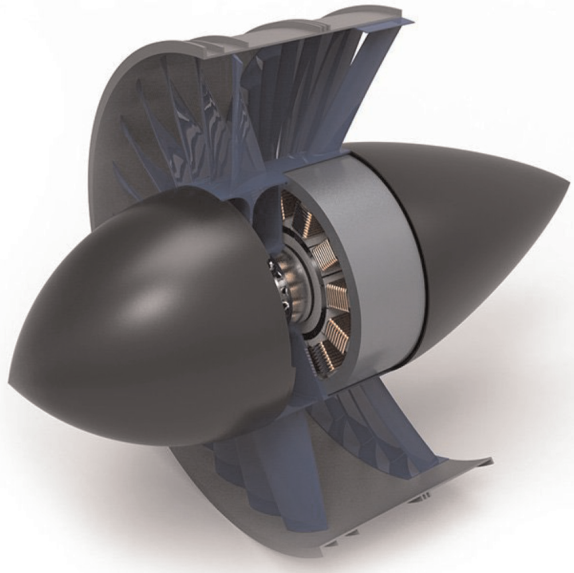

Figure 10.
Lilium electric jet engine [11].

Because the discharge capacity of the batteries did not provide sufficient power at lower levels of the SOC, the battery used permitted a minimum SOC of approximately 30–40%. Modern cell technology employs more advanced anode materials, such as silicon, to increase the battery cell's discharge capacity and, as a result, significantly improves power provision at low SOC. A minimum SOC of 10–15% is enabled for the Lilium Jet, which has seven seats.

Over the years, the performance of the development of battery cells has rapidly improved, and they are now available with energy densities of more than 300 Wh/kg and power densities of more than 3 kW/kg. This helps with the design of a battery system with more than 300 kWh of total stored energy, to achieve a maximum physical range of 250 or more kilometers, including reserves (**Figure 10**).

4. Advantages of electric engines

4.1 Noise

An electric engine is more silent than a motor that combusts fuel. It must drive a rotor, propeller or fan which produces noise during take-off. But electric engines will be quieter when taxiing and cruising. Moreover, distributed propulsion systems with multiple smaller, quieter rotors or fans are also made possible by electric motors.

4.2 Efficiency

Another benefit is efficiency. Compared to today's large turbofans, which are 55% efficient, and small turboprops, which are 35%, electric drivetrains can be more than 90% efficient. One of the reasons why the electrification of propulsion is beginning with the modification of regional aircraft powered is because of the disparity in efficiency between large and small turbines.

5. Disadvantages of electric engines

5.1 Battery

The typical lithium-ion battery is utilized in electric aircrafts can be associated with hazards such as short-circuit and chemical leakage. There are battery chemistries that perform significantly better than current lithium-ion but are not available in the market. The automotive industry is utilizing hydrogen fuel cells and other forms of energy storage. The flow battery, which NASA is exploring for the Aquifer project, is one illustration of novel energy storage within the early stages of development.

5.2 Weight

Super-lightweight carbon-fiber construction methods can be used to make airplanes lighter. A better design can be used to reduce required power. For the longer endurance mission requirements of the largest aviation market segments, a hybrid solution that incorporates a small jet-fuel-powered auxiliary power unit can be utilized. While avoiding the expense and weight of an all-electric battery-powered aircraft, this solution offers improved efficiency at a lower cost. The advantages of electric propulsion will be augmented by jet fuel's high energy density. Additionally, lithium-ion batteries, which are lighter, can be utilized.

5.3 Range

Utilizing electric planes will not be feasible due to their limited range, despite the environmental and financial benefits of not using fossil fuels and the emissions that come with it. Electric planes have the same range as cars on the road, which ranges from 160 to 400 kilometers.

5.4 Thermal runaway

The electrical drive for an aircraft engine must be thermally stable and reliable to pass airworthiness regulations and be deemed safe for flight. Various electrical concepts can be used to design a fully electric aircraft. With regards to the existing electric engine architecture, the motor does not have a robust high torque and insufficient power density under heavy payloads.

6. Electric motor concepts

Table 1 characterizes various electric motor concepts. The permanent magnet synchronous machine is shown as the most suitable design for an electrical architecture (**Figure 11**). However, to qualify and implement this concept, many years of testing and data is required to prove its feasibility (**Figure 12**).

7. Significance of product design

The foundation of product design and development stretches across product architecture, new technology and customer requirements. Product architecture for

Key Characteristic	ESM	IM	SRM	PMSM
Rotor losses	—	o	o	++
Stator losses	++	o	o	o
Windage Losses	—	o	—	++
Rotor thermal limitations	o	+	++	o
Cooling options	—	o	o	++
Rotor mechanical limitations	—	o	+	++
Torque-to-inertia ratio	o	o	o	++
Compatibility with bearings	—	o	o	++
High-speed capability	—	o	+	++
Short-circuit behavior	—	++	++	—
Machine complexity	o	+	++	+
Current density	—	+	+	+
Power density	—	+	+	+

Excited Synchronous Machine (ESM); Induction Machine (IM); Switched Reluctance Machine (SRM); Permanent Magnet Synchronous Machine (PMSM); – unfavorable; — disadvantageous; o neutral; + beneficial; ++ very beneficial.

Table 1.
Key characteristics of various electric motor concepts [12].

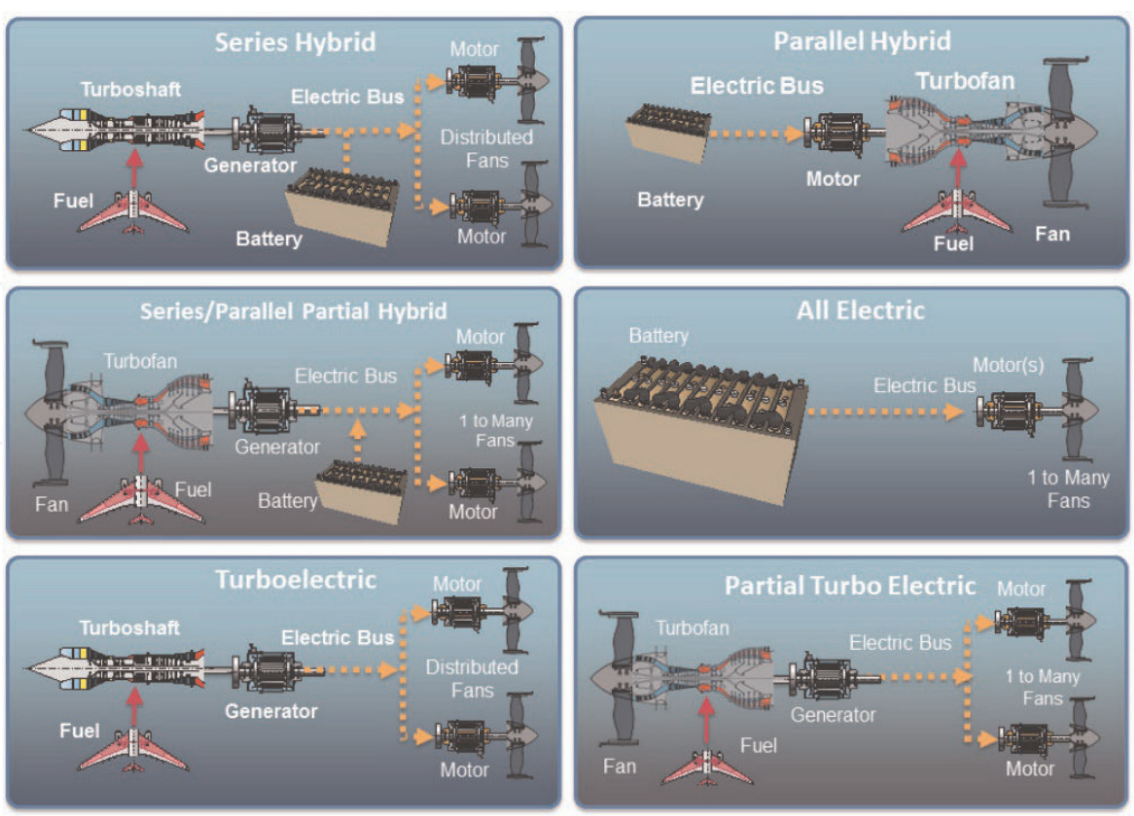

Figure 11.
Schematic of electric propulsion system architectures [13].

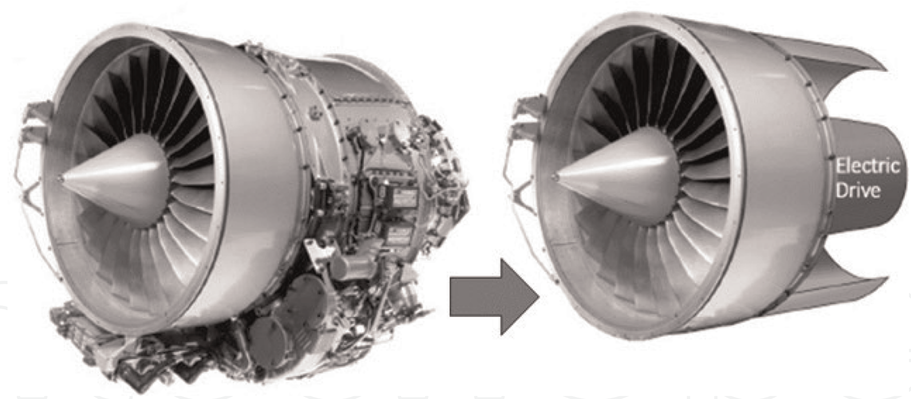

Figure 12.
Substituting an electric drive system in a gas turbine engine (hybrid).

aircraft propulsion design relies on modularity and evolving technologies. The main scope discussed is the future of successful aircraft engine design for the mass transportation market. For strategic technology insertion, the effects of introducing hybrid electric propulsion systems in modern day passenger aircraft will be analyzed.

Different engine modularity and its limitations will be briefly discussed and how it will affect the product development process. Scope and approach give a breakdown on the product lifecycle and when to insert new technology for a successful outcome.

8. The product development process

In product development process, the modular and integral approach is defined to understand in detail the different characteristics involved in reconfiguration for a manufacturing system. Strategic technology insertion and challenges in manufacturing will also be briefly discussed. Product architecture is determined in the early stages of process development. Functional elements are arranged into specific blocks to breakdown their functions (what they do) and how they are interfaced to the rest of the product (**Figure 13**).

Modular approach

i. Functional component elements are mapped

ii. Protocols and interface standards are defined

iii. Component designs are in parallel

iv. Component testing can be done independently

v. Checking for unanticipated coupling and interactions is focused

vi. Required performance changes are localized to a few components

Figure 13.
The product development process.

Integral approach

i. System-Level performance targets are emphasized

ii. Product is divided into few integrated sub-systems

iii. Component tests must be done simultaneously

iv. Effort focused on tuning the overall system

v. Required performance changes propagate to many components

In choosing either one or both two architectural approaches, we need to define the technical working principles and desired variety of features, including setting performance targets. Two indicative definitions are "the ability to repeatedly change and rearrange the components of a system in a cost-effective way" [13] and "the ability of a function of a manufacturing unit to be simply altered in a timely and cost- effective manner" [14].

The reconfigurability of a manufacturing system can be further understood in terms of certain characteristics it exhibits. Modularity is the extent to which all system components; both software and hardware are modular. Integrability is the ability in which systems and components are combined with the introduction of new technology.

8.1 Definition of modularity

The term "modularity" has been widely used to suggest decoupling of construction structures, such that the more decoupled the structures of a product or system, the more modular that product or system will tend to be [15].

$$\text{Component modularity} = \frac{\text{Actual component disconnectivity}}{\text{Maximum likely component disconnectivity}}. \tag{1}$$

Modularity is the extent in which a design system may be split into segments and merged back again. Modularization is intended to effectively redistribute total complexity throughout the system by clustering elements into chunks. A complex modular architecture with multiple modules can result in a dense architecture but should still be advantageous if system decomposability is of major importance. This primarily relates to the effectiveness of using reductionist approaches. Increasing a product's modularity enables these strategies whereas higher complexity makes reductionism less effective.

Modularity is mathematically defined as the extent at which two architectures correspond, on the contrary of intersection. The calculation of correspondence, the Correspondence Ratio (CR), is stated as [16]:

$$CR = \frac{|Vi(x) \cap \mathrm{V}j(x)|}{|Vi(x) \cap Vj(x)|} \tag{2}$$

where |X| points out the number of elements (cardinality) of group X. CR will be near to 1 if the correlation between the two modules is high, vice versa. This is a good way to ascertain module by module foundation, however, does not give good comparison between modules of different designs. A more reliable consideration of module correspondence for an entire product is the average CR for all modules in the product, CRoverall [16]:

$$\text{CRoverall} = \frac{\Sigma CRi}{\#Modules} \tag{3}$$

Likewise, CRoverall = 0 signifies that there is no correspondence between perspectives. CRoverall = 1 when the individual module CRs approaches 1. To convey the second attribute of modularity, reducing minor interactions, a Cluster Independence (CI) is defined [16].

$$\text{Modularity} = (\text{CRoverall}) \times (\text{CI}) \tag{4}$$

8.2 Definition of modularity

Apart from new product introduction (NPI) and managing design changes, strategic technology insertion is one of the important factors in life-cycle management. The three sections where the benefits of a specific technology begin to stagnate are:

i. Technology introduction

ii. Technology improvement

iii. Technology maintenance

In new product development, the critical success factors in descending order of success likelihood are Strong Market Orientation (high), Early Planning and Specification (medium), and Technical and Marketing Excellence (low).

9. Challenges in manufacturing

The main challenges in today's Manufacturing world are customer satisfaction and new technology. Customers have higher expectation for product quality (performance) and on-time delivery at lower cost and shorter time to manufacture. This new paradigm of product development success "to provide the greatest value at the lowest possible cost and shortest time" is hard to achieve and impossible in some situations. The evolving landscape of new technology, digital manufacturing innovation and smart product design influence the strategic decision-making process for both customer and supplier. The lifespan of a new product is shorter nowadays, creating a demand for modularity and commonality weaved together to maximize value and use.

At such an increasing rate of rapid change, the product configuration must be managed strategically so that the organization or business will stand to gain profit and minimize losses. Because of this, most products are designed and built in a fashion that allows it to be remanufactured or reconfigured for reuse, and in certain cases, the quality or performance of the product may be compromised. This is a big concern, especially for reputable companies who have brand reputation at stake. Management finds it difficult to focus on time instead of cost. Period of profitability, time to design, late product launch and competition from rival companies add to the complexity of challenges, where the voice of the customer is always focused on center stage.

10. Design structure matrix (DSM)

This section assesses the methodology of the design structure matrix in terms of modularity and structural complexity. The design structure matrix for three product families to be developed will be used for comparison of the different architectures. The three models are:

i. Old architecture (normal gas turbine engine without a gearbox system)

ii. Existing architecture (geared turbofan engine or hybrid metallic fan blade)

iii. New architecture (hybrid or fully electric jet engine)

The main advantage in mapping out these architectures is to provide a platform to overlay modules and individual parts on the design structure. This ultimately may explain how the different architectures contribute to the product development process through interactions.

The design structure matrix is conceptualized with the modules to provide the means to approach complexity and connectivity between the teams accountable for the design and fabrication of the engine parts. The method in which the design structure matrix was generated is considered in system level decomposition, applicable to all platforms equally. Engine parts selected were dependent upon its functional representation in the system.

In the design structure of the matrix, multiple parts and stages per module were simplified to one. Repetitive units in the system do not add design complexity and hence are not included. Having identified parts significant to the system architecture, relationship of part-to-part components were populated using value mapping and encoding scheme. In **Table 2**, the outlined blocks indicate the 5 modules found by applying the modularity metric. In **Table 3**, the outlined blocks indicate the 16 modules found by applying the modularity metric. In **Table 4**, the outlined blocks indicate the 5 modules found by applying the modularity metric.

11. Product architecture comparison and structural complexity

The three architectures discussed display inherent differences in terms of density and connectivity. This is probably due to the existing architecture having a higher integration of the geared components, packed inside small-scale housing. As a result, structural complexity rises, and can be validated by computed metrics. The structural complexity and modularity metrics were calculated together with interconnections to show variations in their architectural properties. The formula for structural complexity is defined in the following as (**Figure 14**):

Structural complexity distinguishes the system architecture (scheme of interactions), determined by the form. Complexity of the individual components is composed by the total number of α's, to the addition with contribution of complexity due to the number of component interactions and their order. The second term is the

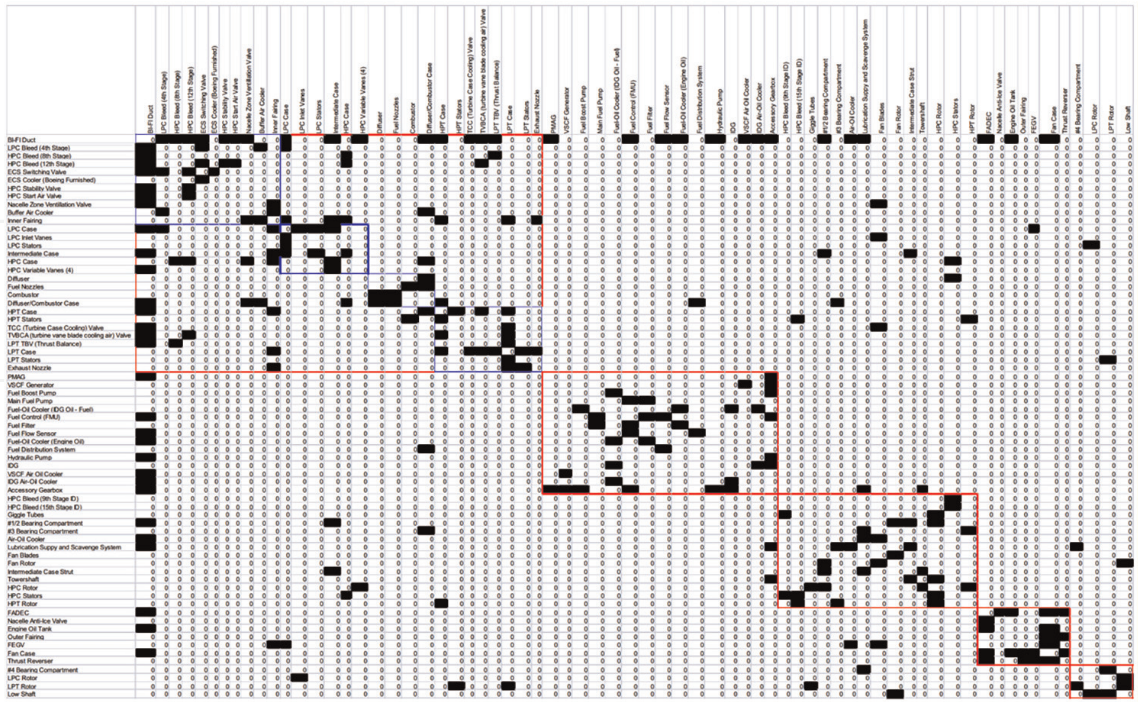

Table 2.
DSM of old architecture [17].

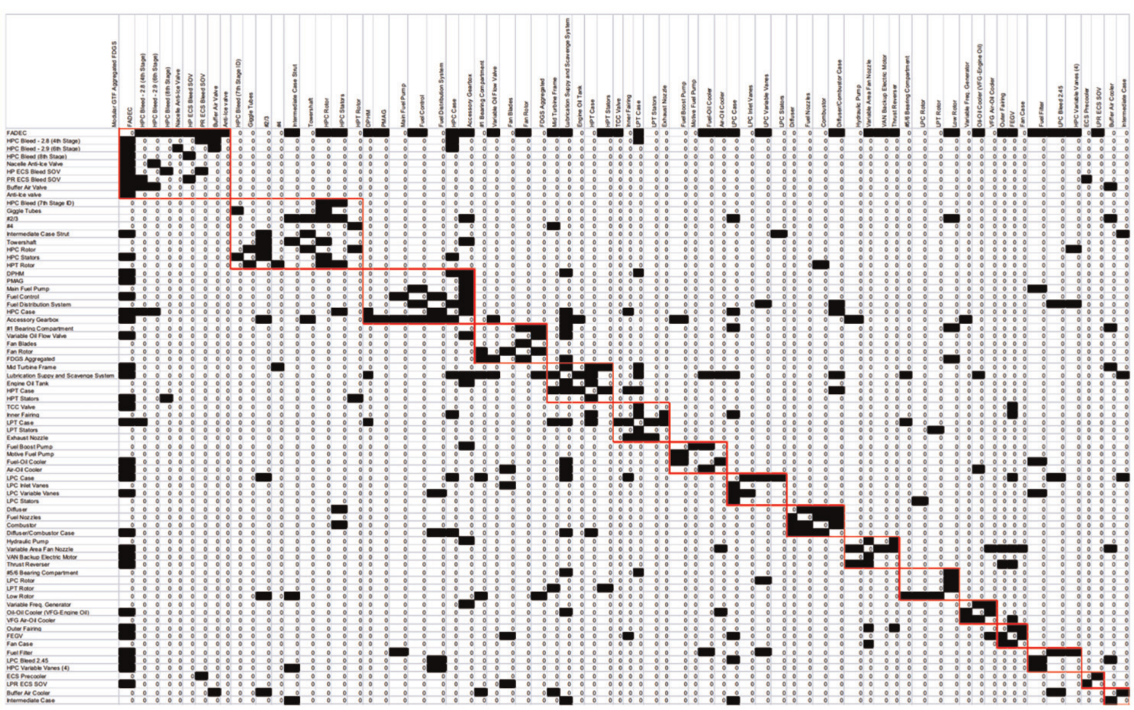

Table 3.
DSM of existing architecture [17].

increased outcome of the total number of interfaces and graph energy. Component complexities are evaluated and exhibit the internal complexity of individual components in the structure (**Figure 15**) (**Table 5**).

	Fan Blades	Fan Rotor	Fan Case	Thrust Reverser	Bearing	Low Shaft	ECU	BCU	MCU	Electric motor	Inverter/converter	Drive & Shield	Switching electronics	Sensors	Brushes & Terminals	Electric cable	Terminal box	Li Battery	Alternator	Charging unit
Fan Blades	0	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fan Rotor	■	0	■	0	0	■	0	0	0	■	0	0	0	0	0	0	0	0	0	0
Fan Case	■	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thrust Reverser	0	0	0	0	■	■	0	0	0	0	0	■	0	■	0	0	0	0	0	0
Bearing	0	■	0	0	0	■	0	0	0	0	0	0	0	0	■	0	0	0	0	0
Low Shaft	0	0	0	■	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ECU	0	0	0	0	0	0	0	■	■	0	0	0	0	0	0	0	0	0	0	0
BCU	0	0	0	0	0	0	■	0	■	0	0	0	0	■	0	0	0	0	0	0
MCU	0	0	0	0	0	0	■	■	0	0	0	0	0	0	0	0	0	0	0	0
Electric motor	0	0	0	■	0	0	0	0	0	0	■	■	■	0	■	0	0	■	0	0
Inverter/converter	0	0	0	0	0	0	0	0	0	■	0	0	■	0	0	0	0	0	0	0
Drive & Shield	0	■	0	0	0	■	0	0	0	■	■	0	0	0	0	0	0	0	0	0
Switching electronics	0	0	0	0	0	0	0	0	0	■	■	■	0	0	0	0	0	0	0	0
Sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	■	0	0	0	0
Brushes & Terminals	0	0	0	0	0	0	0	0	0	0	0	0	0	■	0	■	0	0	0	■
Electric cable	0	0	0	0	0	0	0	0	0	0	0	0	0	■	■	0	0	■	0	0
Terminal box	0	0	0	0	0	0	0	0	0	0	0	0	0	■	■	■	0	0	0	0
Li Battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	■	0	0	■
Alternator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	■	■	0	0
Charging unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	■	■	0

Table 4.
DSM of new architecture.

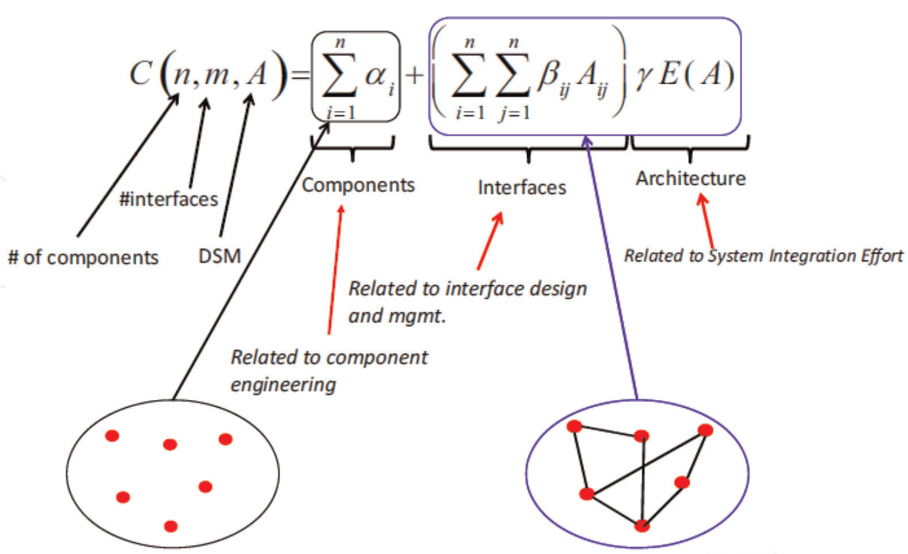

Figure 14.
Structural complexity equation [18].

The DSM for the new architecture shows significantly more connectivity in all areas measured, with a 19% increase in connection density of the DSM. The individual connection types all decreased in number, indicating a less inter-connected

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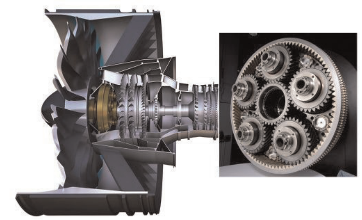
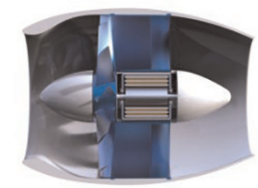
	Old Architecture *Spooled* 	**Existing Architecture** *Geared* 	**New Architecture** *Electric* 	**Change (%)**
No. of Components	71	75	58	−23%
Connection Density	5.75%	6.9%	8.2%	19%
Total no. of Connections	271	363	195	−46%
Mechanical	242	328	183	−44%
Information	49	50	65	30%
Energy	60	62	40	−35%
Flow	89	107	67	−37%
Graph Energy, E(A)	104.4	123.3	136.8	11%
Modularity Index (Q)	0.43 (5 modules)	0.35 (16 modules)	0.62 (5 modules)	77%
Structural Complexity	550	770	320	−58%

Table 5.
Comparison of all three architectures.

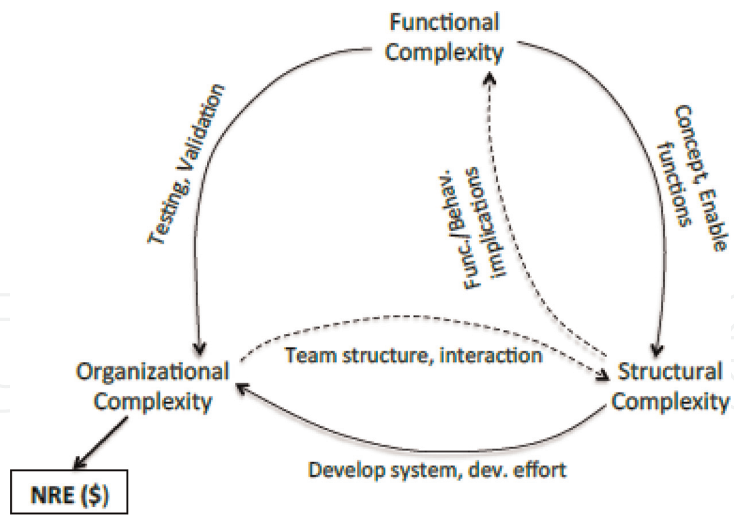


Figure 15.
Main dimensions of complexity in product development [19].

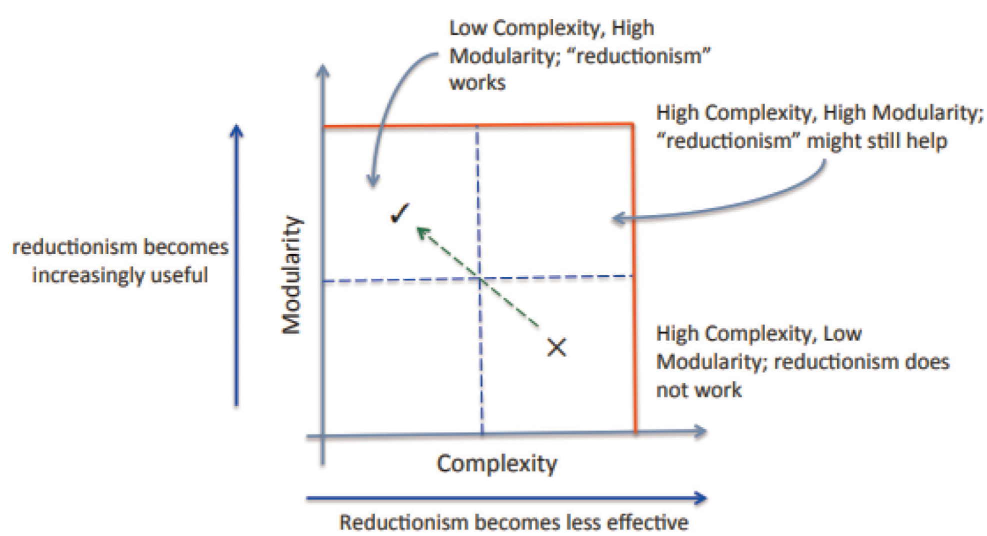


Figure 16.
Complexity-modularity: Impact and effectiveness [20].

architecture. The largest increase, 30%, is found for the information. This lower level of interconnectivity deduces that the electric engine is significantly more "modular", and this is evident in the high modularity (Q) index.

The increase in graph energy E(A), show that the electric system is more distributed than the geared architecture in the table. The modularity analysis demonstrated for the different engine architectures (total connectivity) of the matrix reveal many inherent modules. The electric architecture is significantly less complex.

Figure 15 represents ideal quadrants and its effective zones (low complexity, high modularity) where strategies work well using decomposition techniques to tackle system design and development (**Figure 16**).

12. Conclusion

A high level of modularity in product design is essential if interactions between chunks are well-defined and implemented by individual functional elements. Having a modular architecture enables a design swap chunks independently without affecting the overall system in terms of functionality. The design structure matrix (DSM) developed analyses the various product architectures, comparing existing with new technology. The data suggest that with an increase in connectivity across the components, a balanced distribution in architecture is reached. The decrease in architectural complexity allows a significant increase in low-cost manufacturability.

The correlation between the DSM (architecture) and functional groups can be summarized into two hypotheses for future research. Hypothesis 1: Components with increasing modularity levels are more likely to be more effective in reductionism. Hypothesis 2: Components with increasing complexity levels are more likely to be less effective in reductionism.

From a strategic technology insertion point of view, data such as architectural complexity and integration cost may be useful in business decisions in the development lifecycle. Electrification is gaining significance in futuristic architecture that is bound to disrupt the aviation sector to make the product development process more coherent.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Edgar Jeevan Danaraj
Nanyang Technological University, Singapore

*Address all correspondence to: edgarjee001@e.ntu.edu.sg

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