Amir S. Gohardani
Editor

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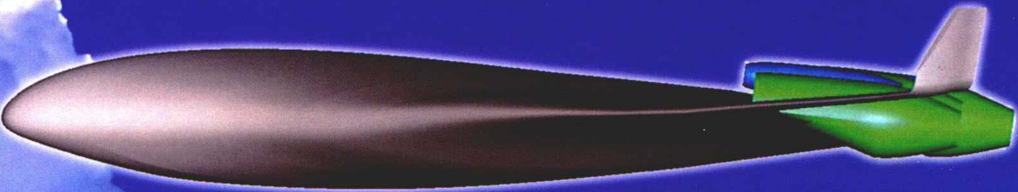

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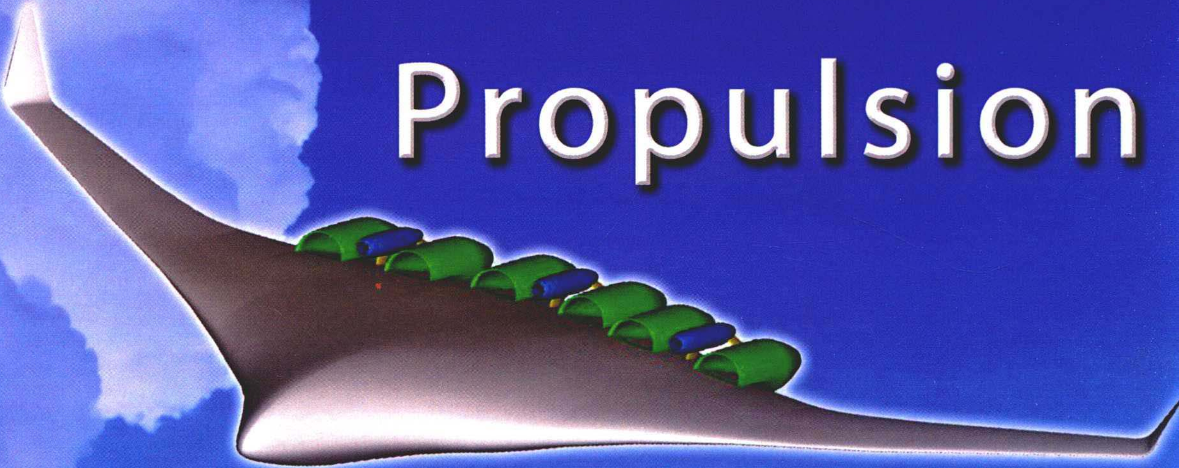

Technology

MECHANICAL ENGINEERING THEORY AND APPLICATIONS

NOVA

MECHANICAL ENGINEERING THEORY AND APPLICATIONS

DISTRIBUTED PROPULSION TECHNOLOGY

AMIR S. GOHARDANI
EDITOR

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PREFACE

Dear Reader,

My very first encounter with distributed propulsion technology was when I was about 4 years old. Looking back, I can surely trace my passion for aeronautical and aerospace engineering to my father who inspired me with his profession as the Head of Technical Inspection Department of Military Aircraft Engines. My father still inspires me and there is nothing more delightful than to spend endless hours discussing aeronautical concepts with him. At an early age, I was intrigued by the number of engines each aircraft had. Why were there a smaller or larger number of engines? What was the rationale? I refused to ask my father these questions, because he would undoubtedly hand over the answers to me on a silver plate. I was of the opinion that I had to find my own answers and this viewpoint ultimately led me to perform the very first set of analysis on Distributed Propulsion Technology (DPT) as a doctoral candidate in aerospace engineering. My review work on DPT led me to the first chapter of this book. Even though the focal point of my doctoral research work was on other aspects of this technology, I was inspired by the historical aspects of DPT. Hence, following my Ph.D. candidancy, I decided to complete my earlier findings with Chapter 2 and to subsequently edit the very first book on this topic, which is represented by the manuscript you now are reading. Apart from my own contributions to Chapters 1 and 2, I have had the pleasure of co-authoring this book with 22 authors from different corners of the globe, thus, the contents of this book represent state-of-the-art DPT arrangements for future air vehicles. The first and the second chapter shed light on the historical traces of DPT and investigate the possibility of this specific technology for the future. Chapters 3, 4, 5, and 6 include DPT contributions from NASA, which has investigated and continue to investigate this technology as a game-changing concept for future aviation. In Chapter 3, a distributed propulsion concept of multiple fans driven by cold compressor discharge air is presented. Chapter 4 showcases a study of a cruise-efficent short take-off and landing aircraft. The aim of this chapter is to examine the feasibility of using many small engines and to enable short take-off and landing operation with low fuel burn in cruise and low community noise simultaneously. Chapter 5 reveals NASA's revolutionary turboelectric distributed propulsion technology concept for blended wing body and hybrid wing body configurations. In the subsequent chapter, three different ultra-high bypass ratio boundary layer ingesting propulsion systems, each integrated onto an 800 passenger blended wing body airframe, are analyzed to determine the net effect on mission range and fuel efficiency of ram drag reduction resulting from ingesting boundary layer flow. Chapter 7 discusses the modeling process of distributed propulsion systems for the conceptual design of transport aircraft, while Chapter 8, unveils a novel motor concept for DPT. Aircraft design, sizing and integration and analysis methodologies for turboelectric distributed propulsion systems featuring superconducting and non-superconducting electrical machine technology are thoroughly discussed in Chapter 9 and Chapter 10. The last two chapters of the book glance at DPT from a macroscopic view. In Chapter 11 DPT is considered as one of the arrangements considered for flow control in advanced gas turbine engines. In the final chapter, the former Chief-Scientist of the United States Air Force shares the science and technology vision for the United States Air Force energy. This book includes a combination of historical milestones, technical data, conceptual aircraft design approaches and state-of-the art technologies that include but are not limited to electric aircraft and superconductivity. The historical journey of DPT across the years is likely to lead us to a future populated with aeronautical wonders. I cordially invite you to join me on this journey.

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Many individuals have contributed to this manuscript, either as authors or reviewers of the authored chapters. In certain instances, a number of the individuals listed on this page have simply supported various efforts related to distributed propulsion technology. I hereby would like to thank the following individuals for their contributions to distributed propulsion technology and for providing me with a global foundation to explore this technology on my own: Nathan C. Barnes, Arthur Palisoc, Keri Dionizio, Max F. Platzer, Kim H. Dae, James L. Felder, H. Douglas Perkins, Leifur Leifsson, Mark T. Maybury, William H. Mason, Joseph A. Schetz, Andy Ko, Keiichi Okai, Hitoshi Fujiwara, Hiroshi Nomura, Takeshi Tagashira, Ryoji Yanagai, Makoto Shibata, Christopher A. Snyder, Franco Frate, Robert Handschuck, James Hunter, Daniel Kosareo, Eric Hendricks, Mary Reveley, Michael Tong, Andrew Gibson, Kurt Patahakis, Jeff Freeman, Julio Chu, Gerald Brown, Ruben Del Rosario, Dennis M. Bushnell, Starr Ginn, Woodrow Whitlow Jr., Arun K. Sehra, Philippe Mason, Mica R. Endsley, and Lesley M. Wright.

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October, 2013, Orange County, California, United States of America

BIOGRAPHY

Dr. Amir S. Gohardani is a Senior Aerospace Engineer at L·Garde Inc., Orange County, California, USA, working primarily on the Sunjammer, Solar Sail Technology Demonstration Mission (TDM) for NASA and as a Project Manager of two different projects related to national security and orbital debris. Before joining L·Garde, Dr. Gohardani worked as a Propulsion-Procurement Manager at OHB-Sweden (formerly Swedish Space Corporation Space Systems Division) in Sweden and at the Aerospace Division of Rolls-Royce University Technology Center in the United Kingdom where he investigated and designed future aircraft, intended for years 2030-2040, in collaboration with Rolls-Royce Strategic Research Center. Dr. Gohardani's space experience involves the Solar Orbiter mission, a joint NASA and European Space Agency (ESA) venture planned for year 2017, in addition to his collaboration with the Swedish National Space Board. Dr. Gohardani's research expertise includes space applications, distributed propulsion technology, green aircraft/space propulsion, electric aircraft, aircraft performance, particle image velocimetry, laser vibrometry, experimental aerodynamics/aircraft design, and experimental heat transfer studies. In 2012, the first official definition for distributed propulsion technology in subsonic fixed wing aircraft was globally presented by Dr. Gohardani. Dr. Gohardani, is a United States Wakonse teaching fellow, the recipient of a once-in-a-lifetime Vertical Flight Foundation graduate scholarship from the American Helicopter Society (Arizona Chapter) along with 20 other national/international scholarships/awards. He has numerously been awarded for teaching excellence in mechanical and aerospace engineering at the University of Arizona. Upon completion of a distinctive teaching program in Learner-Centered Education, Dr. Gohardani was awarded a College Teaching Certificate from the University of Arizona (summa cum laude) in 2008 and was further bestowed the title Honorary Citizen of Tucson, Arizona, United States of America, in the same year. The following year, he was also named among the top six thesis authors in Europe by The European Foundation of Power Engineering. Dr. Gohardani holds Ph.D. and M.Phil. degrees in Aerospace Engineering from Cranfield University, United Kingdom, a M.Sc. degree in Mechanical Engineering from the University of Arizona, United States of America, in addition to a M.Sc. degree in Aeronautical Engineering - awarded after a Visiting Research Scholar position at the University of Florida, United States of America - and a B.Sc. in Vehicle Engineering from the Royal Institute of Technology, Sweden.

CONTENTS

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Chapter 1

CHALLENGES OF FUTURE AIRCRAFT PROPULSION: A REVIEW OF DISTRIBUTED PROPULSION TECHNOLOGY AND ITS POTENTIAL APPLICATION FOR THE ALL-ELECTRIC COMMERCIAL AIRCRAFT

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ABSTRACT

This introductory chapter highlights the role of distributed propulsion technology for future commercial aircraft. After an initial historical perspective on the conceptual aspects of distributed propulsion technology and a glimpse at numerous aircraft that have taken distributed propulsion technology to flight, the focal point of the review is shifted towards a potential role this technology may entail for future commercial aircraft. Technological limitations and challenges of this specific technology are also considered in combination with an all electric aircraft concept, as means of predicting the challenges associated with the design process of a next generation commercial aircraft.

Keywords: Distributed propulsion, All electric aircraft, More electric aircraft, Future commercial aircraft

NOMENCLATURE

E	maximum cargo range (km)
P	power output for each individual engine unit (kW)
R	aircraft range (km)

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T	engine thrust (kN)
V	aircraft speed (km/h)
OWE	operating empty weight (kg)
PAY	payload (kg)
$MTOW$	maximum take-off weight (kg)
NoE	number of engines
ϕ	piston/propeller unit engine power (kW)
ξ	number of engine units
AC	alternating current
AEA	all electric aircraft
AEE	all electric engine
APU	auxiliary power unit
BLI	boundary layer ingestion
BWB	blended wing body
CESTOL	cruise efficient short take-off and landing
CMF	common-core multi-fans
CMP	common-core multi-propulsors
dB	decibel
DC	direct current
DEN	distributed engines
DEX	distributed exhaust
DFRC	NASA Dryden Flight Research Center
ECS	environmental control system
ERAST	environmental research aircraft and sensor technology
ESTOL	extreme short take-off and landing
ETOPS	extended range operation with two-engine airplanes
FAA	Federal Aviation Administration
HALE	high altitude long endurance
HP	horse power
HTS	high temperature superconductive
HALSOL	high-altitude solar energy
HWB	hybrid wing body
IDG	integrated drive generator
LP	low pressure
MDO	multi-disciplinary optimization
MEA	more electric aircraft
MEE	more electric engine
NASA	National Aeronautics and Space Administration
PAI	propulsion-airframe-integration
PFCC	power factor correction number
PM	permanent magnet
PPS	primary power systems
PWM	pulse width modulator
RAT	ram air turbine
RPM	revolutions per minute

SFC	specific fuel consumption
SPS	secondary power systems
SR	switched reluctance
STOL	short take-off and landing
TRU	transformer rectifier unit
TV	thrust vectoring
UHBR	ultra high bypass ratio
VF	variable frequency
VTOL	vertical take-off and landing
VSCF	variable speed constant frequency

INTRODUCTION

The intricate challenges of meeting future environmental goals in commercial aviation require a cross-disciplinary effort that focuses on: feasible propulsion systems, reduced fuel consumption, aviation safety and reliability, noise reduction, and optimized aircraft design to achieve desirable flight attributes.

With a constant increase of air passengers, and the demands for technological innovation to reduce harmful emissions and jet noise, the impact of commercial propulsion systems becomes even more pronounced. Contemporary trends of intelligent engines raise a fundamental question that addresses the most promising propulsion system for commercial aviation and in retrospect, conceptual inventive engine systems are systematically investigated.

The technical lessons learned from aviation history are important venues for future technical progress. One of the many intriguing subjects regarding future aircraft is the visions aviation enthusiasts anticipate for the future. Küchemann's early approach to recognize the need for additional efforts in the aerodynamics of propulsion is noteworthy as prior advances in propulsion technology were indeed extended far beyond the realm of airfoil theory [1]. Küchemann and Weber's comprehensive aircraft performance study at subsonic, supersonic and hypersonic speeds has further served as a gateway for improved understanding of aerodynamic shape and its evolution [2].

Challenges within the hypersonic flight regime are, however, particularly difficult to overcome, as strong shockwaves or disturbances are caused in response to lift generation and other means to provide volume and propulsion [3]. From a general perspective, it is possible to draw parallels between Küchemann's envisioned differences in the design procedures for various aircraft [4] and this study, as both seek to examine at least one particular mode of propulsion in further detail.

Air transport of the 21st century is no longer limited to technological constraints, but also to environmental restraints that in combination with increased flight safety, dictate the nature of future flight regimes and flight missions. Aircraft distributed propulsion is one of the promising propulsion systems currently considered for integration into a wide number of future air transport models. As with any promising system, the limitations and weak points of this technology are identified in light of its strengths and advantages. The aim of this chapter is to make an assessment of aircraft distributed propulsion, with a mindset of environmental awareness. Throughout the scope of this study, an All Electric Aircraft concept is also considered in combination with the distributed propulsion technology, as the electric aircraft trend displays one of the environmental friendly propulsion options for future commercial aircraft.

Distributed propulsion is based on dividing up the thrust for the beneficiary gain of noise reduction, shorter take-off and landing, enhanced specific fuel consumption and flight range. This is particularly true if the complete aircraft history is to be included in this definition, dating back to the early days of flight, where the means of propulsion were different from those of the jet engine era. Figure 1 depicts a few historical milestones of aircraft distributed propulsion.

The planes above and below the time axis categorize aircraft distributed propulsion into a conceptual domain and a manufactured domain, respectively. The conceptual domain revisits a few hypothetical ideas that have contributed to the implementation of aircraft distributed propulsion arrangements. Variation among these different configurations covers, however, a substantial portion of different propulsion system designs that have made it to the manufacturing phase. Many of the known aircraft incorporating distributed propulsion systems are equipped with jet engines.

On the other hand, if distributed propulsion is defined as an arrangement where the units of thrust are spread along the body of the aircraft, then the tracks of this arrangement are traced to a few years prior to the invention of the jet engine.

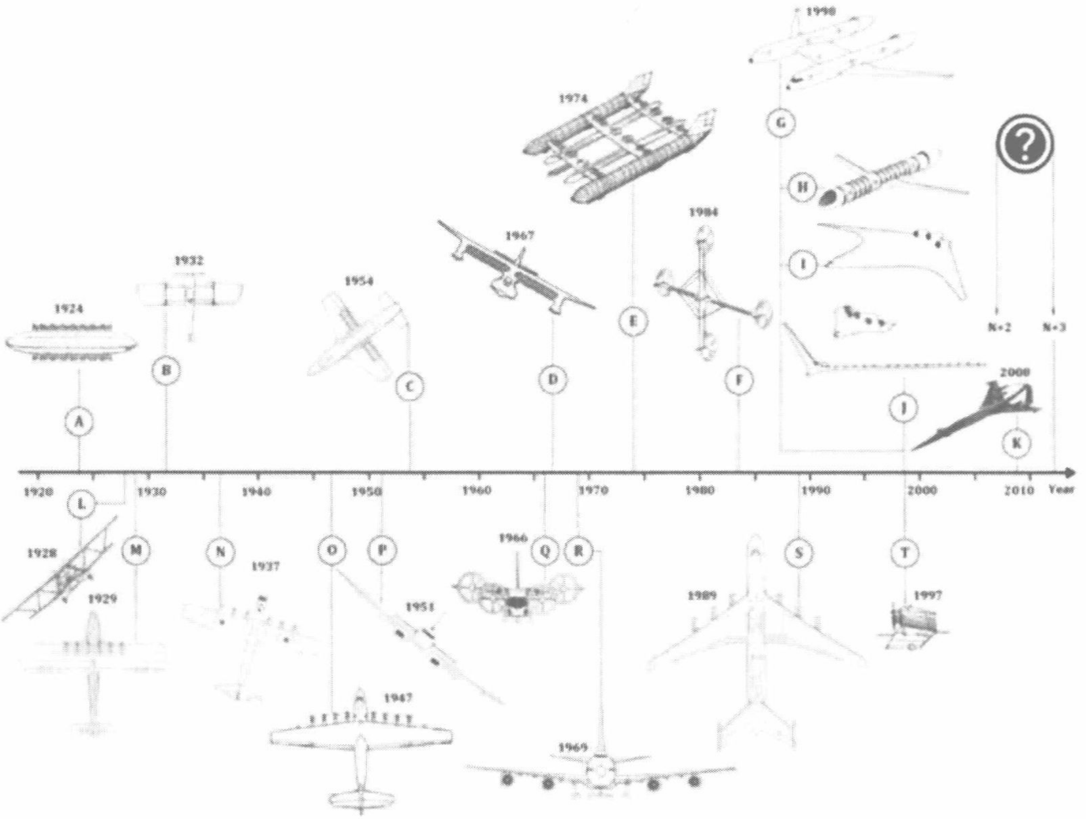

Figure 1. A few conceptual milestones versus actual milestones of aircraft distributed propulsion technology.

HISTORICAL REVIEW OF DISTRIBUTED PROPULSION TECHNOLOGY

A Few Conceptual Milestones of Distributed Propulsion Technology

In 1924, Manzel (Figure 1A) proposed multiple propeller units arranged in two rows or series as the propelling mechanism for airships, aircraft and the like [5]. The motivation behind this concept was the feasibility of ascent without a special landing field. Although the usage of wings, a major contributor to the aerodynamic lifting force, was negligible in this proposal, similar approaches stagnated, and Altieri's invention (Figure 1B) of introducing additional flight power in 1932, was based on using auxiliary propellers fore and aft of the aircraft wings [6]. Recognizing the small effect of supplemental propulsion assistance, using additional propellers, this concept was primarily aimed for proper and safe landings. In 1954, Griffith replaced the earlier propositions of propellers with gas turbines (Figure 1C) and presented the concept of an aircraft with a master combustion engine unit in combination with a number of gas turbine 'slave' units that were spaced in the spanwise direction of the aircraft wing structure [7]. Providing the means for Thrust Vectoring (TV), short take-off and landing (STOL), and low fuel consumption, this invention combined many new technical features of significant potential. Reyle's 1964 proposal (Figure 1D) was related to an aircraft that could use gas turbine technology for the engines disposed between the ducting surfaces and nuclear engines in the engine nacelles, if positioned at a distance from the fuselage [8]. Reyle envisioned that this concept would contribute to power-weight ratio enhancement, but did also recognize radiation concerns in the event of an aircraft crash. A novelty associated with this conceptual scheme was the coupling of two different means of propulsion systems.

Because an additional propulsion unit could jeopardize the entire aircraft, careful attention to reliability was paid to the system. This cast light on one of the principal complexities of combining different propulsion systems. Even though the potential safety risk associated with nuclear power consistently has affected nuclear powered aircraft [9], future nuclear concepts have not entirely been abandoned [10]. Pursuing another research front, Malvestuto Jr. [11] took interest in an aircraft capable of carrying substantial payloads (Figure 1E). Using a wing structure, divided into several wing portions equipped with rotors together with rotors in arrangement with lighter-than-air buoyancy units, this rotor-wing combination distributed the power over a much larger effective area to achieve considerably higher power loadings, in comparison to a conventional power loading of a helicopter. As a result, distributed propulsion was also considered and introduced for Vertical Take-Off and Landing (VTOL) aircraft. One could argue that this concept brought Manzel's concept (Figure 1A) to a new level, using a wealth of knowledge that was gained over almost 60 years. Referring back to an initial core idea, the new arrangement and position of propellers in another plane contributed to new features and an illustration of conceptual evolution is traceable in a new proposal presented by Phillips [12] in 1983. In this conceptual proposition (Figure 1F) a solar powered aircraft was considered with a cruciform wing structure.

Equipped with solar cells and multiple propellers positioned on the wingtips, details were provided on how to maintain surfaces normal to the Sun's rays to utilize the direct solar energy. This concept, amongst others, served as a crucial step towards the development of solar airplanes, such as the first generation High-Altitude Long Endurance (HALE) vehicle, Pathfinder [13]. The discovery of the Antarctic Ozone Hole, earlier that decade, also boosted the need for further stratospheric research programs related to high-altitude aircraft, under the Environmental Research Aircraft and Sensor Technology (ERAST) [14] alliance, initiated by NASA and the industry. In 1988, NASA proposed a number of detailed concepts [15] for airframe and propulsion interactions and integrations. A commonality between these concepts (Figure 1G–J) is the employment of different propulsion systems. SnAPII (Figure 1G) featured twin fuselages separated by a circulation-control wing that contributed to high lift coefficients during takeoff and landing. Using two tail-mounted engines at the end of each fuselage with TV and reversing, fuselage Boundary Layer Ingestion (BLI), and smart inlet and nozzle technology, SnAPII also used a device to power flow control on the outer portions of the wing. Wing tip turbines could further reduce the wake hazard at takeoff and landing. This concept merged two individual fuselages with their propulsive units into one main body.

A hypothetical scenario of total engine failure for either one of the combined fuselages was simplified in the subsequent proposal for a distributed engine (Figure 1H) regional STOL aircraft. This airplane made use of an array of wing-integrated mini-engines to provide lift augmentation and distribution with increased redundancy. Employing another array of mini-engines at the tail, integrated with inlet and nozzle, deflectors enabled the Coanda effect for TV. Using a similar circulation-control wing similar to SnAPII, a blended forward-swept wing body concept was envisioned (Figure 1I). This aircraft used three aft-mounted high-bypass ratio turbofans with BLI, TV and reversing, smart inlet, nozzle technology and flow control systems. Trans-Oceanic Air-Train, (Figure 1J) was characterized by two vehicles, the Lead and the Mule. These vehicles rendezvous to complete the cruise configuration of a long range transport of cargo. Although the design was aimed at freight flight in the low transonic regime, in favor of high aspect ratio wings and span loading for minimal fuel consumption, parts of this concept could potentially also be applied to commercial aviation. Equipped with TV-technology for optimal take-off performance, the Lead vehicle was designated as the primary fuel carrier and responsible for flight control activities of all Mule vehicles. All unmanned Mule vehicles incorporated pylon structures with morphing technology and powered by advanced ducted prop pylons, carrying enough fuel for takeoff, rendezvous, connection, abort and landing. Rendezvous between different aircraft that would transport future air travelers from point A to B, pose new unexplored propulsion challenges. Nonetheless, these concepts cannot be disregarded because of their levels of complexity.

Most of the proposals, presented in this short journey throughout the conceptual milestones of aircraft distributed propulsion, have dealt with the subsonic flight regime. However, this does not imply that supersonic concepts were neglected or never proposed. In fact, the perspectives and demands for rapid air travel also point to the supersonic flight regime. 2008 marks the year when Lockheed Martin, in collaboration with other industrial partners and academic institutions, envisaged a future aviation concept, operational between the years of 2030 and 2035 [16]. Implementing synergistic combinations to tackle flight emissions, fuels and airport noise, the artist's rendering of this concept shows a (Figure 1K) distributed propulsion system and an environmentally friendly airframe system aimed for supersonic operation. However, it can also be argued that this supersonic concept only features four engines. Since a distinct definition regarding the distributed propulsion terminology is not readily available, a placement of an aircraft with four engines within the distributed propulsion category would only hold if the definition of this technology indeed referred to an aircraft employing three engines or more. The short glimpses of implemented technologies in the conceptual milestones of aircraft distributed propulsion have revealed the use of hydrogen, piston engines, gas turbines, solar cells, electrical units and nuclear power, in various arrangements for aircraft propulsion. Despite the random chosen order of these concepts, these multi-faceted propulsion tools exhibit many configurations that have been integrated into a variety of manufactured aircraft. Thus, it is important to revisit a few milestones of aircraft distributed propulsion that have partially been the fruit of thought from these referred concepts.

A Few Milestones of Aircraft Employing Distributed Propulsion Technology

A common theme instilling the conceptual time line of distributed propulsion marks the dawn of various aircraft that employed available propulsion units of their time for new technical arrangements. For the purpose of elucidating ideas that became reality, a short visit is made along the historical axis of time, to point out some aircraft that implemented three or more units of propulsion and were chosen for commercial, experimental, cargo, research and military applications. Unlike the early days of conceptual aviation where distributed propulsion was introduced in the airship industry, many promising proposals that would have progressed into production were never funded. One possible cause for this, at least in the latter part of the 20th century, emerged from the misconception that hydrogen was the primary cause of the Hindenburg catastrophe [17]. Doubtlessly, the term 'Hindenburg syndrome' [18] had a negative influence on the general public and the airship industry, but regardless of this significant impact, the aviation industry embraced many different designs featuring distributed propulsion. In 1929, Dornier Do X (Figure 1M), the world's largest aircraft at the time, flew for the first time [19]. Intended for transatlantic flights, this aircraft left Friedrichshafen, Germany, on 2 November 1930 with 17 passengers and crew for the USA. After eventful flights via a few European cities, Brazil, the West Indies, and Miami, the aircraft reached New York on 27 August 1931. Equipped with faired-in engine supports for its 12 engines, Dornier Do X also suffered many delays enroute to New York and many of these were related to technical difficulties. Early long range flight attempts with distributed propulsion revealed many unforeseen parameters that could not be efficiently addressed or investigated during the conceptual design phase.

Engine cooling was one of these problems. Using multiple engines without any cooling measures caused a thrust reduction for the rear engines. Conversely, the combination of distributed propulsion and commercial aviation appeared to have its own advantages. The same year the Dornier Do X aircraft left Friedrichshafen, Handley Page H.P.42 (Figure 1L), made its first flight [20]. Intended for the purpose of linking various parts of the British Empire, this aircraft used two engines on each of the large unequal-span biplanes, leaving a brilliant record of safety with no fatal accidents after a decade of service. An innovative part of H.P.42's design was to position the propulsion units on different wings. Seemingly a successful trend for long-range missions, multiple engine solutions were chosen more often and this involved also two historical flying boats. The first aircraft, Blohm und Voss BV 222 Wiking (Figure 1N), the largest operational flying-boat during World War II, was specifically designed for long-range passenger transport in the late 1930s and was equipped with six vertically opposed engines distributed over the wing [21]. Following this success, a historical flight was made by Howard Hughes' famous H-4 Hercules (Figure 1O) in 1947. H-4 Hercules was the largest flying boat ever built and consisted of a single hull and eight radial engines

[22]. Taking into consideration the significant size of the aircraft, a substitution of wood for metal served as a new gateway for non-conventional approaches to aircraft design. The design practices of this aircraft revealed, however, many technical difficulties ranging from the intergration of power system to large control surfaces. These problems added a new dimension to the earlier observed difficulties with engine cooling procedures in aircraft distributed propulsion. During the transition to the jet engine era, the Avro Type 706 Ashton Mk 3 aircraft (Figure 1P), equipped with either five or six turbojet engines, initially flew in 1951. It was principally used for research purposes. An interesting feature of the employed distributed propulsion system in Ashton Mk 3 was the wing- embedded scheme. The Bell D-2127 aircraft (X-22) (Figure 1Q) took the concept of distributed propulsion one step further with its tilting arrangement of ducted fans. 1966 was the first time this aircraft took to the skies and almost two decades later it had contributed significantly to the VTOL/STOL research through programs at NASA and Federal Aviation Administration (FAA) [19]. Various relations between the distributed technologies in the Bell D-2127 and Ashton Mk 3 aircraft could certainly be generalized to conceptual models. In the majority of all considered cases (along the time line in Figure 1), ideas adopted on both planes, complemented each other regardless of sequential order.

1969 was the year when the Boeing 747 aircraft (Figure 1R), perhaps one of the most commonly known historical airplanes in commercial aviation, had its first flight. The Boeing 747 used four turbofan engines in pods pylon-mounted on wing leadings edges. Equipped with air-cooled generators mounted on each wing for electrical supply, two additional generators could provide primary electrical power when the engine-mounted generators were not operational [19]. Technological advancement and the Boeing 747's efficient propulsion system integration were evident in a blunt comparison to the Dornier Do X's engine mishaps. The engine arrangement on the Boeing 747 has become a standard configuration for many commercial aircraft. Although the number of engines in some cases has been reduced to only two for other aircraft, this was not the case for the Antonov An-225 MRIYA aircraft (Figure 1S) which was not designed to transport air travelers, but rather to transport the Soviet space shuttle. In 1989, Antonov An-225 completed this task with its six engines fitted with thrust reversers and glass fiber engine cowlings [19]. Nine years later, two distributed propulsion systems were combined in a propulsion scheme with virtually no harmful emissions. Centurion (Figure 1T), an unmanned solar-powered aircraft, first flown in 1997, with 61.8 meters wingspan and 14 brushless direct-electric motors, could reach altitudes of 30 km. Envisioned as the 'Eternal Airplane' with the objective to fly for months, solar arrays were used to power electrical motors [23]. The environmental impact of this aircraft has contributed to considerations for more environmentally friendly propulsion systems. The next section aims to identify a number of these trends for commercial aviation.

Historical Trends of Distributed Propulsion Technology for Selected Commercial Aircraft

Given the random nature of the chosen aircraft in the previous section, an interesting approach would be to consider a larger population of aircraft and derive a few historical trends of distributed propulsion technology. For this specific purpose, aircraft characteristics of 70 commercial aircraft employing at least three engines, as an indicator for the distributed