FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Towards Sustainable Product and Supply Chain Development in the Aerospace Industry

Nuno Bernardo Gonçalves Falcão e Cunha

Leaders for Technical Industries Doctoral Program

Supervisor: Pedro Sanches Amorim

Co-Supervisor: Bernardo Sobrinho Simões de Almada-Lobo

March 22, 2022

Towards Sustainable Product and Supply Chain Development in the Aerospace Industry

Nuno Bernardo Gonçalves Falcão e Cunha

Leaders for Technical Industries Doctoral Program

March 22, 2022

Information and Funding

Submitted to Faculdade de Engenharia da Universidade do Porto in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Industrial Engineering and Management, supervised by Pedro Amorim, Assistant Professor at Faculdade de Engenharia da Universidade do Porto, and Bernardo Almada-Lobo, Full Professor at Faculdade de Engenharia da Universidade do Porto.

This research was supported by the PhD grant PD/BD/114379 Ref.ªCRM:0026749 awarded by the Portuguese Foundation for Science and Technology (FCT) under the MIT Portugal program.

This research was also part of Work Package 4 entitled "Supply Chains Towards Sustainability" within the IAMAT project for the Introduction of Advanced Materials Technologies for the Mobility Industries. This project was developed in tandem with Universidade do Minho, Universidade do Porto, Universidade Técnica de Lisboa and MIT. This project was awarded grant MITP-TB/PFM/0005/2013 from the Foundation for Science and Technology (FCT).

“Success is going from failure to failure
without losing your enthusiasm.”

Winston Churchill

Abstract

The optimisation of air transport has demanded innovation from all echelons of the aerospace supply chain. The introduction of new materials and production technologies reshaped supply chain structures, and redefined responsibilities for both original equipment manufacturers (OEMs) and their suppliers. Thus, to prevent disruptions arising from these transitions, all stakeholders must incorporate sustainability measures into their planning strategies. This thesis aims to assess the sustainability (including economic, environmental and social sustainability) and uncertainty in the development, sourcing and procurement methods of current and previous aircraft. For this purpose, mathematical tools are proposed as decision support tools, suitable for each of these stages. To improve the reliability and applicability of these tools, these models were used in two collaborations with academic and industry partners. In the context of overall sustainability assessment an integrated framework is proposed to map new trends, make supply chain design decisions, assess sourcing performance, and optimise sustainability metrics. Furthermore, a mathematical programming model for concurrent product and supply chain design with proactive supply chain risk management for integration risk is developed. This model is validated using real data from a large European OEM. Finally, a demand model is implemented to measure the impact of sustainability specifications on the demand from commercial airlines. The results from each model provide valuable insight for all companies involved in producing and managing air transport assets, but can also be applied for industries and supply chains with similar characteristics and challenges.

Resumo

A otimização do transporte aéreo exigiu inovações a todos níveis na indústria aeroespacial. A introdução de novos materiais e tecnologias de produção reformulou a estrutura das cadeias de abastecimento e redefiniu as responsabilidades, tanto dos fabricantes do equipamento original (OEMs), como dos seus fornecedores. Assim, para evitar disrupções associadas a estas transições, é fundamental que todos os agentes incorporem medidas de sustentabilidade nas suas estratégias de planeamento. Deste modo, a presente tese pretende medir a sustentabilidade dos métodos de produção, seleção de fornecedores e abastecimento, para aeronaves atuais e passadas. Com este propósito, a tese desenvolve ferramentas de apoio à decisão, adaptadas a cada uma das referidas etapas. Com o fito de melhorar o grau de fiabilidade e a aplicabilidade destas ferramentas, estes modelos foram implementados em duas colaborações com parceiros académicos e da indústria. No contexto da avaliação global de sustentabilidade (incluindo sustantabilidade económica, ambiental e social), é proposta uma estrutura integrada capaz de mapear novas tendências, tomar decisões de desenho de cadeias de abastecimento, avaliar o desempenho no abastecimento e otimizar as métricas de sustentabilidade. Além disso, é desenvolvido um modelo de programação matemática para o desenho simultâneo de produtos e cadeias de abastecimento, com gestão proativa de riscos de cadeias de abastecimento para o risco de integração. Este modelo foi validado com dados reais de um grande OEM Europeu. Por fim, é implementado um modelo de previsão de procura, a fim de medir o impacto de especificações sustentáveis na procura por parte das companhias aéreas. Os resultados de cada modelo permitem tirar conclusões relevantes para todas as empresas envolvidas na produção e manutenção de meios de transporte aéreo, sem prejuizo do facto de poderem também ser aplicados a indústrias e cadeias de abastecimento com características e desafios semelhantes.

Acknowledgements

First and foremost, I would like to thank Past Nuno for all the hard work, for his resilience, for all the sleepless nights and, most of all, for not giving up. It is thanks to all the decisions he made along the way that I am able to come out at the other end of this PhD and see that what I've learnt in the past few years goes well beyond the content of these pages.

I want to thank my father for his incessant support, in the brightest days and darkest nights, and for always knowing whether I needed to be comforted or if a bit of shock therapy was in order. The disbelief he first showed when I was accepted to join the LTI program quickly evolved into unassailable conviction that I would see this through.

To my mother and brother who accompanied me through very challenging times. For their persistent concern with my well-being, and for being the most active bridges connecting me to the rest of the family, who also provided immense support.

In the final stages of my PhD, Joana was my lighthouse, keeping me focused and confident on reaching the end of my thesis. As she became one of the most important people in my life, she brought a tidal wave of motivation and constantly reminded me that I was the only one with any doubts that I'd reach this goal. No matter how hard I had to push to get here, she always had the right mindset to keep me going. She has my gratitude and my admiration.

I must extend a very special thank you to my supervisors, Professor Pedro Amorim and Professor Bernardo Almada-Lobo. Since the beginning, they introduced themselves as my colleagues, they were formidable mentors, and became invaluable friends. Thank you for always finding the right way to challenge me and to keep me going.

Thank you Thiam-Soon Gan and Professor Martin Grunow for welcoming me in Munich and truly introducing me to the German culture and to the aerospace industry. They ignited my interest in this field. Eduardo Curcio was also fundamental during this process. A note of gratitude for his patience and all the hours he spent with me in front of the white board.

Friends keep you sane and make you want to keep moving forward. Thank you to my oldest friends, and biggest fans, my grandparents.

Thank you to the Skype Group for all the support and for always showing me that the gathering is the most important part of life.

Nuno Bernardo Gonçalves Falcão e Cunha

Contents

List of Figures

List of Tables

Abbreviations and Symbols

AHP	Analytic Hierarchic Process
ATAG	Air Transport Action Group
CGF	Cumulant Generating Function
CO_2	Carbon Dioxide
CP-SCD	Concurrent Product and Supply Chain Design
DES	Discrete Event Simulation
DSS	Decision Support System
DST	Decison Support Tool
EU	European Union
GIS	Geographic Information System
ICAO	International Civil Aviation Organisation
IP	Intellectual Property
IAMAT	Introduction of Advanced Materials Technologies for the Mobility Industries
IRM	Integration Risk Matrix
MGF	Moment Generating Function
MIP	Mixed Integer Programming
MIT	Massachusetts Institute of Technology
MMO	Maximum Operating Speed (in Mach Number)
MRO	Maintenance, Repair and Operations
NDT	Non-Destructive Testing
NPD	New Product Development
OEM	Original Equipment Manufacturer
PD	Product Design
PDF	Probability Distribution Function
PSM	Part-Supplier Matrix
RHS	Right-Hand Side
RO	Robust Optimisation
SCA	Supply Chain Architecture
SCD	Supply Chain Design
SCR	Supply Chain Risk
SCRM	Supply Chain Risk Management
TBL	Triple Bottom Line
TUM	Technical University of Munich

Chapter 1

Motivation and Overview

The aerospace sector has redefined the transportation paradigm and has become one of the most prominent and globalised high-tech industries, both in terms of manufacturing and market structure [Reis, 2011]. The sector has seen an exponential growth for nearly seventy years, but has been highly susceptible to global phenomena such as the events of 9/11 and the 2008 global financial crisis. More recently, according to IATA [2020], the worldwide COVID-19 pandemic has reversed twenty years of growing demand for commercial flights. Historically, commercial aircraft OEMs have recovered from these events by introducing new materials, production technologies or by adapting their supply chain architecture [Tang et al., 2009]. To do so, companies must be able to maximise the sustainability of these transitions, model their effects, and gauge the demand for those products. Silva et al. [2020] report that, prior to 2020, the main priorities for aerospace and defence companies were on improving manufacturing, digital transformation, supply chain, product strategy, and overall sustainability. Post-COVID, there is no expectation for these to change significantly, except for a higher focus on innovation. This means businesses will seek solutions to boost their efficiency and sustainability in developing new products.

On the manufacturing front, OEMs have looked for new materials technologies to reduce their aircraft's operating costs, improve impact resistance, and reduce the effects of fatigue from repeated cycles. The latter trends also aim to decrease costs and downtime associated with the incurring inspections and maintenance over the aircraft's lifespan. The use of composite materials has been one of the most prominent innovations. Mrazova [2013] explains how this technology stands to improve aircraft performance in all of these metrics, including the reduction of the aircraft's weight and the resulting lowering of their fuel consumption. Composite materials are also much more resistant to impact and fatigue than their metallic counterparts. The corollary being that these materials stand to improve the environmental sustainability of the aerospace sector. They simultaneously mitigate CO_2 emissions, and improve the recycling potential of aircraft parts, as indicated by Yang et al. [2012].

Along with the new supply chain challenges that follow the introduction of disruptive technologies, new materials have also demanded improved NDT techniques from OEMs. For example, Schnars and Henrich [2006] details how composite parts can be rendered unusable due to delamination and debonding, porosity and foreign body inclusion.

Within the scope of the second major trend for the aerospace industry, digital transformation, OEMs have been pursuing digitalisation, along with improved data analytics through AI. Read [2020] reports that data is being used to enhance all stages of the aerospace value chain, from design and manufacturing to delivery, in-service, modifications, recycling and reuse of aircraft. There is also an emergent trend of creating digital twins of physical aircraft, which can be used to both analyse their performance and maintenance requirements, but also to plan improvement of subsequent models. Furthermore, digitalisation has changed the MRO landscape, which now includes real time monitoring of the entire process and wearable tech with augmented reality to facilitate engineering assistance.

For over a decade, commercial aircraft OEMs have addressed supply chain and product strategy concurrently. Many major aerospace programs have transitioned into multinational, risk-sharing business models. Aiming to spread non-recurring costs (e.g., design and development, and manufacturing certifications) which have represented most of their financial exposure, OEMs have begun to share PD and production responsibilities with suppliers (e.g., Boeing 787, Airbus A350). In addition, new manufacturing technologies have also led to new product architecture and supply chain structure. There is a trend towards more modular products and supply chain designs that require greater integration [Berger, 2015, Deloitte, 2018], as well as industrial capabilities to manage integration projects. As future aircraft programs face increasing costs and shorter life cycles, Alfalla-Luque et al. [2013] and Michaels [2020] both report the emergence of a new generation of super tier-1 suppliers. These suppliers take on the role of system integrators and consolidate technical and supply chain management responsibilities.

This type of supply chain design has incurred unforeseen expenses and delays caused by the quick transition of engineering and management commitments to inexperienced partners. This is especially critical for the aerospace industry as integration involves assembly of different types of components (e.g., airframe, electrical, electronics, dynamic). For example, wrong product interface definitions may lead to assembly issues and unclear supply chain interface definitions (e.g., forecasting method, ordering policy) between different echelons of the supply chain. Currently, there are no quantitative risk management methods employed in tandem with PD and SCD. Additionally, the current risk classifications within the SCR literature do not address this source of uncertainty in supply chain planning.

All of these innovations can be linked to the sector's macro-trend in seeking sustainability, be it economic, environmental, or social (e.g., ethical sourcing of raw materials). However, stakeholders across the entire value chain are faced with a difficult trade-off between sustainability practices and their customers' business interests. Aligning these motivations is a complex endeavour, especially for commercial airlines. In 2019, the global aviation industry was responsible for 12% of CO_2 emissions from all transport sources, whereas road transport accounts for 74%. However, aircraft travel averages nearly seven times the emissions in grams of CO_2 per passenger per kilometre. To address this issue, the ATAG [ATAG, 2021], an association of agents from the entire industrial sector, announced its goal of halving CO_2 emissions by 2050, compared to the ones measured in 2005. The ATAG also committed to halt the rise of net emissions by 2020. Even though the COVID-19 pandemic led to an abrupt decrease of these emissions, this effect is temporary and current reports suggest a return to the 2019 air traffic by 2023 [Bouwer et al., 2021]. For commercial operators, this commitment has increased the complexity of fleet selection and management decisions. Airlines must combine criteria from multiple domains. On one hand, they must seek to minimise CO_2 emissions, fuel consumption, maintenance requirements, and even noise. On the other, when assigning an aircraft to a route, they must look at seat capacity, maximum take-off mass, and aircraft range.

The focus of this thesis is on providing companies in the aerospace industry with decision support tools to enhance the sustainable development of new material technologies and the incurring supply chains. The models can be applied in different industry echelons and were developed to address planning challenges, product and supply chain modularity, integration uncertainty, and product planning for new aircraft programs. Thus, while this thesis does not look at specific manufacturing techniques, or digital transformation, it provides insights for the optimal adoption of these technologies while capturing all other major trends for the aerospace sector.

1 Research Objectives and Methodology

This research aims to develop decision support tools for the aerospace industry that can enhance the sustainability of the introduction of new materials and technologies, and handle the uncertainty associated with these transitions. This will be achieved by improving the efficiency and extending previous methodologies and by combining existing approaches from other industries and fields of research.

To map and understand sustainability challenges for the aerospace industry, two international collaborations were established. The first venture was within the IAMAT project, combining three Portuguese universities with MIT, focusing on the development of sustainable supply chains capable of fostering the aforementioned materials technologies. Another project was developed in partnership with TUM, looking at the recent trend of supply chain integration for aerospace OEMs. Both collaborations involved large industry partners provided data and insight into what the models should be looking to solve. Understanding current challenges also demanded reviews of qualitative analysis on the industry's evolution and disruptions, as well as quantitative models that have been employed to handle those issues.

The shift towards integrated supply chains with tier-1 suppliers acting as system integrators highlighted two gaps in the literature. First, the need for a new SCR type that translates integration risk. Second, a SCRM methodology that acts in tandem with PD and SCDE. RO is an emergent approach to study uncertainty from risk sources with unknown probability distribution profiles. RO has been used to incorporate uncertainty into mathematical programming models in multiple areas of operations research, including the problem of supplier selection [Kisomi et al., 2016, Rabieh et al., 2018]. As such, RO is employed as an extension to an collaborative PD and SCD model, which has been optimised.

While there is extensive qualitative literature on sustainable fleet management and aircraft product strategy, there is limited quantitative analysis on the airlines' priorities. Discrete choice models have been previously used to estimate how airlines value aircraft specifications. These models can also be used to estimate each characteristic's contribution to the aircraft's market share, and predict how the introduction of a new model can affect the demand for the remaining products. However, there have been no new studies for nearly twenty years, they considered mostly demand within the USA, and did not take into account sustainable attributes such as noise or fuel consumption.

The centre piece of this research is the sustainable development of new materials, technologies and supply chains. The relationship between each research question is presented in Figure 1.1. Research question 0 (RQ0) was at the centre of the large IAMAT collaboration and drove the ensuing research questions and models. Research questions 1 (RQ1) and 2 (RQ2) relate to the shift toward system integrators which highlighted the lack of proactive SCRM mechanisms when OEMs pursue disruptive shifts in supply chain configuration. The

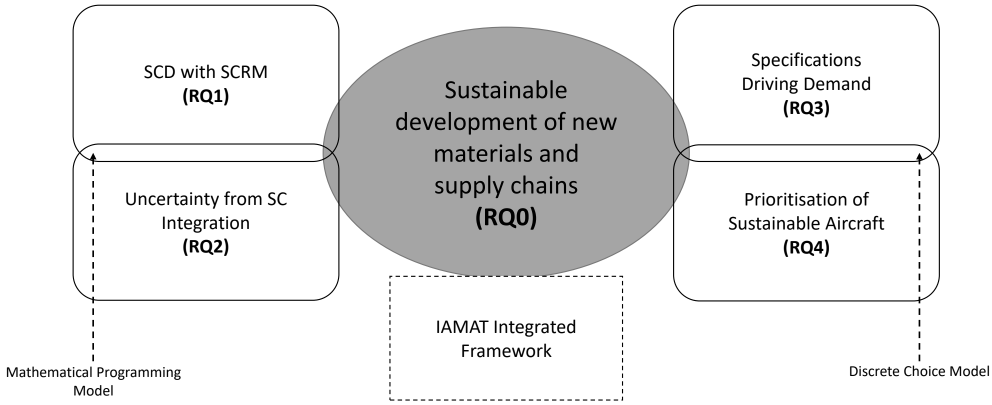


Figure 1.1: Framework for research questions.

mathematical programming model employing PD. SCD with selective sourcing flexibility, integration risk mitigation and RO answers these questions and is part of the framework designed to answer research question 0 (RQ0). Research questions 3 (RQ3) and 4 (RQ4) test the downstream impact of sustainability decisions made by OEMs and their supply chains.

Research Question 0 *How can the development of new products and supply chains be improved in terms of sustainability, for the aerospace sector?*

This research question arises from the need for an integrated framework for the improvement of supply chain sustainability capable of accounting for economic, environmental and social objectives. OEMs must identify and react to novel supply chain challenges associated with the introduction of new products and emergent technologies. The goal is to maximise the effectiveness and sustainability of R&D efforts by providing OEMs with the appropriate tools to rethink and adapt their operations.

To answer this research question, a decision support system with four collaborative tools will be presented: mapping of supply chain strategic evolution and new trends, supplier integration risk management, supply chain performance assessment, and supply chain design and planning optimisation. The results from these models will be used to plan the introduction of advanced materials technologies into new product development for the mobility industries.

Research Question 1 *How to model and solve concurrent Supply Chain Design and Supply Chain Risk Management decisions?*

This research question is motivated by the nonexistence of a mathematical model capable of making SCD decisions while incorporating SCRM measures. While works in the literature on these two topics includes methodologies to address them independently, their interface has only been addressed qualitatively. Reports of issues arising from the lack of proactive SCRM practices acting in tandem with systems design and supplier selection have highlighted the need for a quantitative tool. However, previous models for SCD such as Gan et al. [2021] are not sufficiently efficient for this extension.

The outcome of this research question will be a mathematical programming model capable of assembling supply modules with concurrent systems design, supplier selection decisions and risk mitigation mechanisms. The model selects the number of supply modules the sourcing flexibility therein based on the risk threshold imposed by the decision maker during the SCD process. The results will provide managerial insight for industries with convergent supply chains, and will be validated using a real case study from the aerospace industry.

Research Question 2 *How to address uncertainty in the performance from suppliers acting as System Integrators using Robust Optimisation?*

This research question is built on the recent risk exposure from OEMs making the transition towards system integrators, and the growing popularity of RO to deal with uncertainty in optimisation problems for which the uncertain parameters have an unknown probability distribution. This analysis highlighted a gap in the literature for SCR and led to the definition of a new SCR type, termed the integration risk, combining disruptions associated with the technical and managerial capabilities assigned to this new generation of suppliers.

The outcome of this research question will be three different approaches to incorporate integration risk in the SCD process, resulting in a model for robust SCD. The results investigate the trade-off between integration and risk exposure, and suggest the ideal supply chain integration levels according to the decision maker's risk aversion profile. To improve the applicability of this tool for industries with converging supply chains, further results were drawn using probabilities of constraint violation by assigning asymmetric triangular distributions to the uncertainty variables. This methodology has been suggested as the best fit for industries that have "educated guesses" on the most likely values for their uncertainty variables.

Research Question 3 *How are aircraft specifications driving the demand from commercial airlines?*

This research question is motivated by a gap in the literature on the most valuable aircraft characteristics for commercial operators. The only regression work this topic is Irwin and Pavcnik [2004]. However, this work uses a limited data set, and has now also missed nearly twenty years of development for the aerospace sector. Moreover, as the focus was on the impact of subsidies in aircraft pricing, previous models considered very few independent specifications.

To answer this research question, a discrete choice model will be built to estimate the contributions from different aircraft characteristics to the utility function for commercial airlines. By introducing price as a dependent variable, it will also be possible to observe The multinomial logit regression model will predict market share contributions from each of independent variable. Moreover, these results will make it possible for OEMs to estimate the market share captured by new aircraft, and how it will affect sales for other models.

Research Question 4 *What is the impact of sustainability commitments on the evolution of fleet management practices?*

This research question is investigated following stakeholders across the entire value chain in the aerospace sector making commitments to pursue sustainability targets, in particular in terms of CO_2 emissions. However, there have been no quantitative studies on whether the sustainability driven specifications of aircraft, such as noise reduction or fuel consumption are driving demand, or if route specific attributes such as available seating or range are driving the demand from commercial airlines.

To answer this research question, the evolution of the prioritisation given to different independent aircraft specifications over the years will be studied. This requires extensive data collection of aircraft sales across more than 60 years, along with the characteristics for each aircraft model. A discrete choice model will rank the importance of the competing attributes to the utility function for commercial aircraft operators over the years.

2 Thesis Structure and Synopsis

This thesis is comprised of a collection of papers. Research question 0 is answered in Chapter 2, Chapter 3 is aligned with research questions 1 and 2, Chapter 4 answers questions 3 and 4. This section outlines the contents of each chapter and the main findings therein.

Chapter 2 describes the main output from the IAMAT collaboration between the University of Porto, the University of Minho, the Technical University of Lisbon, and MIT. This project also had a large South American OEM from the aerospace sector as an industry partner. The paper entitled "Towards an Integrated Framework for Aerospace Supply Chain Sustainability" was written within the scope of Work Package 4, entitled 'Supply Chain Towards Sustainability'. The goal of this research was the development of generic tools for defining and evaluating supply chain impacts of product design choices embedding sustainability concerns. To enhance the sustainable development of new products and supply chains, a four-tiered decision support system was developed that considers economic, environmental and social sustainability. Firstly, methodologies for mapping trends and major stakeholders within the aerospace sector are introduced. Then, a collaborative product and supply chain design model is proposed. This model is explained in detail and extended in Chapter 3. The tool also includes a hybrid simulation performance assessment mechanism suitable for analysing sustainability trade-offs is sourcing and manufacturing of parts with new materials or processes. Finally, a mixed-integer programming model is employed to optimise sustainability metrics and improve the computational time of the remaining simulations.

Chapter 3 defines a new SCR type, termed the *integration risk*, which is based on the OEMs' estimations of each supplier's technical capabilities for manufacturing parts and producing integrated components, along with their ability to manage their downstream supply chain. To answer research question 2, a mathematical programming model is proposed for concurrent product design, supply chain design and supply chain risk management. This model is an extension to the work in Gan et al. [2021], to include integration risk and supply chain risk management. To make this adaptation possible, the model had to be optimised so it could achieve feasible solutions in reasonable time frames. This model also builds on the insight from Tang et al. [2009] which attributed the disruptions associated with the aerospace integrated supply chains to the lack of proactive SCRM measures working concurrently with SCD. The model does not analyse integration of aerospace supply chains into consolidated supply modules as a binary decision. Instead, in order to mitigate the OEM's risk exposure, the model provides solutions with different integration levels, i.e. number of supply nodes/modules, and decides the sourcing flexibility for each of those modules. Each module can be single or double sourced. Since the literature on integration-related issues has only been described qualitatively, three distinct exploratory approaches were implemented to assess and mitigate risk exposure. These modelling approaches make it possible for decision makers to vary the resolution with which they deal with risk, by looking at the overall supply chain, at supply node level, or by disallowing individual part-supplier assignments.

To answer research question 2, Chapter 3 goes on to introduce RO to deal with uncertainty associated with the integration risk estimations made by OEMs for their supplier pool. These estimates are gathered in an IRM, which may be incorrect depending on how well the OEM knows the supplier's operations, and may also vary throughout the aircraft's life cycle. For each approach, RO introduces Γ-values which represent the percentage of IRM values that have deviated from their original values. These are taken to be the baseline values and are susceptible to change either due to an incorrect estimation associated with lack of information, or due to a change in performance over time. Depending on their risk aversion, decision makers are tasked with electing the risk threshold for the risk mitigation mechanism they choose to implement. Furthermore, the model solves the product and supply chain design problem based on their confidence on the values compiled in the IRM. Since estimating how many of those values are likely to be incorrect is not a trivial exercise, an alternative procedure for solving the model is suggested. To enhance the applicability on the industry side, an extension to RO was considered based on Guzman et al. [2016], Guzman et al. [2017a] and Guzman et al. [2017b]. By assigning triangular asymmetric probability distribution functions to the risk values, it is possible to equate probabilities of constraint violation to different realisations of uncertainty. This provides decision makers with an additional dimension to adjust the model to their needs.

Chapter 4 answers research question 3 through a discrete choice demand model for commercial airlines, building on past examples from the literature. The data collected to build this model includes approximately 29,000 aircraft acquisitions, with nearly 180 different aircraft models, over the last sixty years. These transactions correspond to the top one-hundred commercial airlines which also include the top twenty low cost commercial operators. The demand model estimates the utility for airlines from each of the aircraft's specifications. For this analysis, the characteristics gathered included fuel capacity and maximum range (in conjunction, these attributes provide insight on fuel consumption), noise, passenger capacity, maximum take-off and landing weights, and cruise and maximum speeds. As suggested by Irwin and Pavcnik [2004], the model admits different market segments for commercial aircraft, such as wide-body and narrow-body aircraft. The tool goes on to test the difference in priorities for traditional airlines and low cost carriers.

Furthermore, aiming to answer research question 4, Chapter 4 tests the market's alignment with commitments made by stakeholders across the entire aerospace value chain. This is achieved by analysing how the weights for each of the available aircraft specifications over the years. By solving the model for acquisitions from different time periods, it is possible to check whether fuel consumption and noise have been given increasing importance in recent decades.

Chapter 5 provides an overview of the main findings and contributions within this thesis, along with the answers to each research question, and considerations on future work.

Bibliography

Rafaela Alfalla-Luque, Carmen Medina-Lopez, and Heribert Schrage. A study of supply chain integration in the aeronautics sector. *Production Planning & Control*, 24(8-9): 769–784, 2013.

ATAG, 2021. URL https://www.atag.org/component/news/?view=pressrelease&id=120. [Online; accessed 6/5/2021].

Roland Berger. Aerostructure equipment market: Study report. Technical report, Roland Berger, 12 2015.

Jaap Bouwer, Steve Saxon, and Nina Wittkamp. Mckinsey & company. back to the future? airline sector poised for change post-covid-19, Jun 2021. URL https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-covid-19. [Online; accessed 2/7/2021].

Deloitte. 2018 global aerospace and defense industry outlook. on a solid profitable growth path. Technical report, Deloitte, 2018.

Thiam-Soon Gan, Moritz Steffan, Martin Grunow, and Renzo Akkerman. Concurrent design of product and supply chain architectures for modularity and flexibility: process, methods, and application. *International Journal of Production Research*, pages 1–20, 2021.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: I. unknown probability distributions. *Computers & Chemical Engineering*, 84:568–598, 2016.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Ii. a priori bounds for known symmetric and asymmetric probability distributions. *Computers & Chemical Engineering*, 101:279–311, 2017a.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Iii. exact and near-exact a posteriori expressions for known probability distributions. *Computers & Chemical Engineering*, 103:116–143, 2017b.

IATA. Covid-19 - outlook for air transport and the airline industry. Technical report, IATA, 11 2020.

Douglas A Irwin and Nina Pavcnik. Airbus versus boeing revisited: international competition in the aircraft market. *Journal of international economics*, 64(2):223–245, 2004.

Meysam Shafiei Kisomi, Maghsud Solimanpur, and Ali Doniavi. An integrated supply chain configuration model and procurement management under uncertainty: a set-based robust optimization methodology. *Applied Mathematical Modelling*, 40(17-18):7928–7947, 2016.

Kevin Michaels. Three predictions for the post-covid aerospace supply chain. *Aviation Week & Space Technology*, October(15-25):74, 2020.

Maria Mrazova. Advanced composite materials of the future in aerospace industry. *Incas bulletin*, 5(3):139, 2013.

Masood Rabieh, Mohammad Modarres, and Adel Azar. Robust-fuzzy model for supplier selection under uncertainty: An application to the automobile industry. *Scientia Iranica*, 25(4):2297–2311, 2018.

Bill Read. Aerospace digital transformation, May 2020. URL https://www.aerosociety.com/news/aerospace-digital-transformation/. [Online; accessed 1/7/2021].

Anabela Costa Reis. *The Aerospace Industry: a Descriptive and Prospective Empirical Analysis for Portugal*. PhD thesis, Dissertação (Mestrado em Engenharia Aeroespacial). Instituto Superior . . . , 2011.

Ulf Schnars and Rudolf Henrich. Applications of ndt methods on composite structures in aerospace industry. In *Proceedings of the Conference on Damage in Composite Materials, Stuttgart, Germany*, pages 18–19, 2006.

Neranjana de Silva, Stephan Baur, Robert Thomson, Manfred Hader, Jan Gerrit Köchling, Kai Balder, Barry Neal, Oliver Hazimeh, Zhanfu Yu, Didier Bréchemier, and et al. Aerospace & defence management issues radar 2020, Dec 2020. URL https://www.rolandberger.com/en/Insights/Publications/Aerospace-Defence-Management-Issues-Radar-2020.html. [Online; accessed 6/5/2021].

Christopher S Tang, Joshua D Zimmerman, and James I Nelson. Managing new product development and supply chain risks: The boeing 787 case. In *Supply Chain Forum: An International Journal*, volume 10, pages 74–86. Taylor & Francis, 2009.

Yongxiang Yang, Rob Boom, Brijan Irion, Derk-Jan van Heerden, Pieter Kuiper, and Hans de Wit. Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification*, 51:53–68, 2012.

Chapter 2

Sustainable Introduction of Advanced Materials Technologies

Towards an Integrated Framework for Aerospace Supply Chain Sustainability

Cátia Barbosa[*†] · **Nuno Falcão e Cunha**[*†] · **Carlos Malarranha**[‡] · **Telmo Pinto**[§] · **Ana Carvalho**[‡] · **Pedro Amorim**[*†] · **M. Sameiro Carvalho**[§] · **Américo Azevedo**[*†] · **Susana Relvas**[‡] · **Tânia Pinto-Varela**[‡] · **Ana Cristina Barros**[*] · **Filipe Alvelos**[§] · **Cláudio Alves**[§] · **Jorge Pinho de Sousa**[*†] · **Bernardo Almada-Lobo**[*†] · **Josá Valério de Carvalho**[§] · **Ana Barbosa-Póvoa**[‡]

Published in *IO'2018 Conference Proceedings*

Supply chains have become one of the most important strategic themes in the aerospace industry in recent years as globalisation and deep technological changes have altered the industry at many levels, creating new dynamics and strategies. In this setting, sustainability at the supply chain level is an emerging research topic, whose contributions aim to support businesses into the future. To do so the development of new products and the response to new industry requirements, while incorporating new materials appears as a path to follow, which require more resilient and agile supply chains, while guaranteeing their sustainability. Such supply chains will be better prepared for the future complex challenges and risks faced by the aerospace companies. Such challenges are addressed in this work, where an integrated framework is proposed to contribute to the resilience and sustainability of aerospace supply chains. Using different analysis methods, the framework addresses four important challenges in the context of aerospace supply chain sustainability: evolution and new trends, performance assessment, supplier selection, and supply chain design and planning.

Keywords: Aerospace Industry · Supply Chain Management · Sustainability · Integrated Framework

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal
‡ CEG-IST, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
§ Centro ALGORITMI, Escola de Engenharia, Universidade do Minho, Braga, Portugal

1 Introduction

Over the years, major aircraft manufacturers have evolved into integrators of complex sets of parts, systems and large modules manufactured by third-party companies [Beelaerts van Blokland et al., 2010]. This sets many challenges for the industry, with the introduction of new materials playing a critical role [Tang et al., 2009]. Understanding the implications at supply chain level brought by the introduction of these materials, and their impacts in terms of sustainability is fundamental [Renn, 2015]. The time and high costs associated with these changes to the aerospace industry are one of the major open issues for aerospace manufacturers and their respective supply network. Clearly, alternative methods to exploit new materials in a more efficient way must be developed [Slayton and Spinardi, 2016]. Future supply chains, in addition to being sustainable, must be resilient and agile in responding to new industry requirements, especially when dealing with new materials.

The IAMAT project (Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries) was launched to address these industry challenges and involves four universities, two companies and different fields of study. Its main goal is to develop an integrated methodology that facilitates the introduction of new materials in the aerospace industry. This paper explores one of the main research lines of the overall project concerning the development of decision support tools to improve supply chain systems aiming at ensuring their sustainability and resilience in the presence of uncertainty.

In the context of this project, we intend to develop a framework integrating various qualitative and quantitative decision support tools to analyse different problems in the context of aerospace supply chain resilience and sustainability. This research paper describes each building block of the framework within the overarching IAMAT project. The remaining sections include the underlying motivation (section 2), and, in section 3 , the description of the integrated framework, as well as the methodologies for each of the tools within it. Section 4 highlights the projects main contributions and how the aerospace industry stands to benefit from it. Main conclusions and future research directions are also depicted in this section.

2 Motivation

As mentioned in Section 1 , major aircraft manufacturers have evolved into system integrators, outsourcing most aircraft parts as large integrated modules from key supply partners. As a result of the markets pull for more efficient aircraft, OEMs had to rethink their products which, in turn, led to a revolution within the incurring supply chains. To boost the effectiveness of R&D efforts, OEMs delegated considerable product design, development and manufacturing responsibilities to their suppliers. The other main reason behind this approach was to share the non-recurring costs in new aircraft programs, thus reducing the exposure of the OEM. These emerging super tier 1 suppliers entered risk sharing partnerships with OEMs and only began to receive returns on their investments after the aircraft was being sold. The biggest step in this direction was taken by Boeing when 70% of 787 Dreamliner's production was delegated to 50 strategic partners, which were called Integrators [Tang et al., 2009]. This paradigm has proven challenging to suppliers who have had to quickly develop their technical and managerial capabilities.

Concurrently, growing sustainability concerns in the aerospace industry, along with pressure from airlines, have been pushing OEMs to improve the efficiency of their aircraft and of their supply chains [IATA, 2013]. While attempting to reduce aircraft operating costs, and CO_2 emissions from worldwide air traffic, aerospace OEMs have been engaging in NPD programmes. They have prioritised the weight reduction of aircraft by using advanced materials in aerostructures and the improvement of engine efficiency [Tang et al., 2009]. Our goal is to provide OEMs with decision support tools that seek to minimise the impact on sustainability performance associated with the introduction of new advanced materials and technologies.

The general structure of the aerospace supply chain can be visualised in Figure 1, and it has been derived from the works presented in ICF [2012] and Mocenco [2015]. It consists of four supplier levels and the OEM as the responsible for the final assembly. The tier 4 suppliers are responsible for supplying the materials to be processed throughout the chain. The components suppliers, tier 3, use the raw materials to produce simple components that are assembled with other components or integrated in major aerostructures at tier 2 and tier 1 levels. Tier 1 and tier 2 suppliers can be classified according to the type of structures being supplied, assuming an interchangeable role. While for integrated structures, suppliers assume a tier 1 role, for sub-assemblies, suppliers assume a tier 2 role. In an attempt to improve the aircraft efficiency, these suppliers often engage in adopting new manufacturing processes and using new materials. The OEM is responsible for the assembly of the aircraft, the highest value product in the whole chain. However, this is not the only responsibility of the OEM, it must also control and set the supply chain architecture considering the supplier risks. The sustainability of the aerospace supply chain can only be globally addressed through the cross-tier supplier analysis and assessment of industry evolution and trends. Figure 2.1 also shows the scope of each of the tools within the framework.

3 Integrated Framework for the Improvement of Supply Chain Sustainability

As identified in the introduction section, the aerospace supply chain is currently facing many sustainability challenges. This calls for the integration of solution approaches that

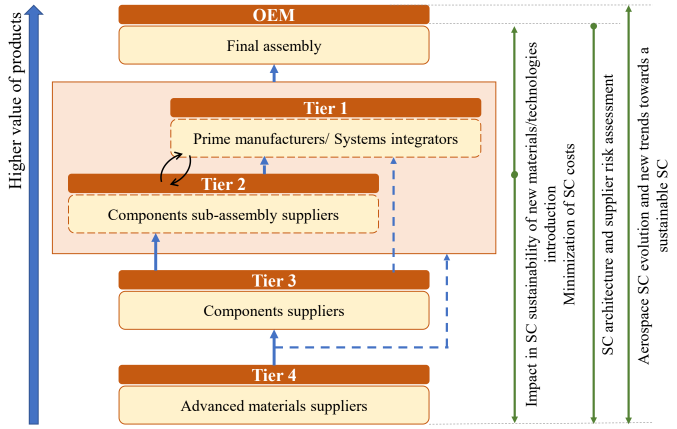


Figure 2.1: General structure of an aerospace supply chain.

can respond to the different problem requirements, while in an integrated way provides a pathway for improving the overall aerospace supply chain sustainability, particularly during NPD initiatives with the introduction of advanced materials/manufacturing processes.

Figure 2.2 presents the proposed integrated framework that builds on the sustainability challenges and considers a TBL as the trigger for the improvement of the business value. The bottom of the pyramid (1) frames both the evolution and the new trends of aerospace supply chain. Additionally, they aim to identify and characterise the supply chain stakeholders, while mapping the connections among them and assessing their engagement and main priorities towards sustainability. These supply chain strategic analytical tools based on the new trends are the input to the higher levels of the framework that consider the SCD. Qualitative research methods have been used for a global and conceptual supply chain analysis, such as systems thinking and content analysis.

Rising in the framework levels, appears the second group of tools, (2), that proposes concurrent product and SCD considering the supplier's integration risk. This tool uses both qualitative and quantitative approaches by introducing risk management practices into the process of selecting suppliers and using RO techniques. This tool allows managers to assess the danger of disruptions caused by the introduction of new technologies, and their outsourcing practices. While this tool gives an overview of a selected supply chain architecture for the physical supply chain analysis performed by the upper levels of the framework, it gives important risk assessment inputs to the lower framework level. The integration of the risk assessment enhances the development of the sustainable supply chain concepts at the lower level.

The third group of tools, (3), deepens the working principles of the aerospace supply

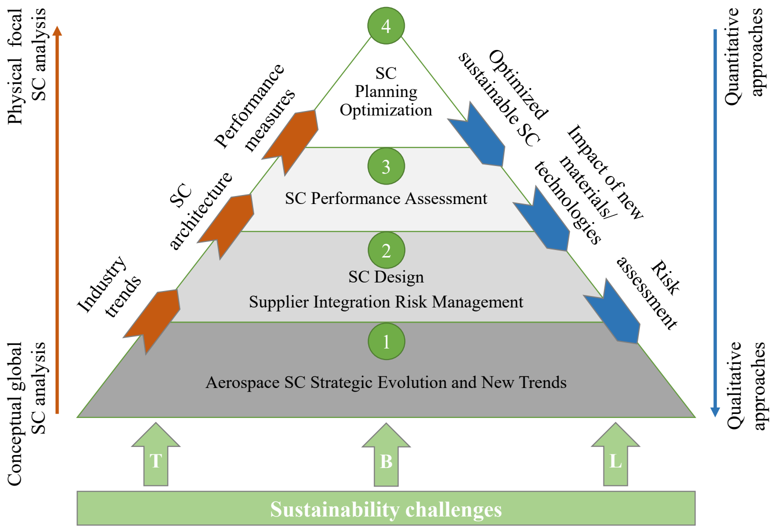


Figure 2.2: The integrated framework.

chain, by integrating the supply chain architecture proposed by the lower level tool. Using a simulation approach to achieve a dynamic analysis of the supply chain behaviour, the hybrid simulation models, by integrating different levels of analysis at the supply chain nodes, allow extracting relevant performance measures predictions for comparing the impact of using different advanced materials and manufacturing processes. The relevant measures assessed serve as input to be integrated in an optimisation tool at the upper framework tool, and can be used to narrow the number of possible supply chain participants to be considered at the concurrent product and SCD level. The hybrid simulation models make use of quantitative methods for the model development and integrate a trade-off assessment of the relevant metrics to be considered.

At the top of the framework lie the MIP models (4), that are quantitative tools for the design of a sustainable supply chain. It builds on the mapped performance measures from the hybrid simulation tool to minimise the overall supply chain costs and environmental impact, while maximising the social value created. This tool assesses the performance of final supply chain configurations, and provides the optimised design, given the constraints arising from the lower framework levels.

From the top to the bottom of the proposed framework, the scope of the aerospace supply chain sustainability analysis is broadened. Different levels of analysis are targeted, providing a cross-functional decision support tool that tackles the prominent needs of the aerospace supply chain and contributes for the analysis and setting of policies towards a more sustainable development. The following subsections provide a more detailed description of how each of these tools addresses current issues in the aerospace industry.

3 .1 Aerospace SC Strategic Evolution and New Trends

The competitive context of commercial aerospace industry has been changing rapidly over the last two decades, and supply chains have become an important driver for NPD, where sustainability concerns need to be guaranteed. OEMs and aerospace supply chains have faced various challenges and have developed several strategic responses in the context of NPD [Tang et al., 2013, 2009]. New challenges and responses will emerge in the future and will continue to have a high impact in the various stakeholders involved and in the sustainability of aerospace supply chains [Oliver Wyman, 2015, Roland Berger, 2016]. Thus, it is important to know how aerospace supply chain has evolved and what the new trends towards a sustainable supply chain are. It is also mandatory to know the most relevant stakeholders towards sustainability, and how to promote their engagement in this purpose.

To answer the question related with the evolution and new trends three mixed methodologies were used: systems thinking, content analysis and comparative analysis (Figure 2.3). Systems thinking approach is used to structure the problem, while content analysis helps to understand how authors have been exploring the questions carried above. Finally, the comparative analysis is carried out involving the four most important aerospace companies worldwide, in a new product development situation. Based on this analysis stage, two conceptual models were defined. The first proposed conceptual model will allow companies to understand the evolution of aerospace supply chains in a NPD context and explore the informations output. The second explores the integration of the critical characteristics of the aerospace supply chain, such as collaboration and system integration with their new trends towards the development of new products accounting for economic, environmental and social objectives.

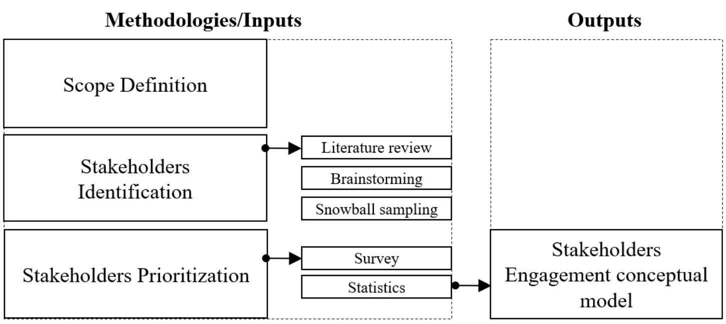


Figure 2.3: Strategic evolution and new trends methodology.

In this context, sustainable supply chains have been recognised as a key element of organisations [United Nations, 2015], encouraging the interest of several stakeholders in recent years. Building a sustainable supply chain and be recognised as a sustainable industry are however major challenges to the commercial aerospace industry. Aerospace supply chains are continuously evolving concerning strategies making the process unstable and uncertain and dependent of multiple and powerful stakeholders with its own views. Aircraft new product development cycles and the new development approaches are crucial in this field. The development of an airplane has become so complex that has led to an increasingly dependency on a network of a large supply chain that involves customers, suppliers, scientific communities, regulators, governments and many others. The subjects related with stakeholder engagement had therefore become critical to evolving and building the sustainability strategies [Bombardier, 2018]. In this context, and as stated above, there is a need to identify the main stakeholders in the aerospace supply chain and their priorities and engagement towards a sustainable supply chain. For this purpose, a multimethodology was explored to allow an integrated stakeholders analysis leading to a conceptual model that helps to frame stakeholders engagement. The multimethodology includes the application of three tasks: scope definition, stakeholders identification and stakeholders prioritisation, which are supported by five methods: literature review, brainstorming, snowball sampling, survey and statistics. Finally, the proposed conceptual models enables a complete stakeholders analysis, recognising sustainability engagement flows among the most important stakeholders while improving the collaboration processes to derive a strategy towards a sustainable supply chain.

3 .2 Robust Concurrent Product and Supply Chain Design under Supplier Integration Uncertainty

Adapting the methodology for CP-SCD described in Gan et al. [2017]. We propose a model that seeks an efficient and robust supply base with minimum number of supplier modules. Supplier modules hold the supplier, or group of suppliers, from which a set of parts is sourced, as an integrated component module. In recent years, OEMs have delegated onto their tier 1 suppliers the development and integration of large component modules. With the introduction of new materials and processes, suppliers are sometimes incapable of complying with the target specifications, which is represented in the new model as the SIR. One of the main extensions proposed in this model is the consideration of each supplier's integration risk in SCD. This uncertainty will be represented in the model as a risk factor. The IR is an input of the model and should result of an assessment of the supplier's technical expertise, as well as own supply chain management capabilities. The aim of the model is to mitigate supplier modules that exceed certain risk thresholds, defined by the decision maker. Another particular aspect of the model is the selective sourcing flexibility for each module, which is a decision variable within the problem.

The first necessary input for the model is the PSM which matches the complete pool of supplier candidates to the set of parts required for the aircraft program. The PSM matches the two sets via a binary relation, and indicates whether the part can be sourced from a certain potential supplier. To each of these connections corresponds an IR for the supplier to integrate that part. The value associated with this risk is compiled in an IRM. The total risk in a module will be the sum of the IR of each component integrated by the suppliers assigned to it. The IRM is another input for the model and contains evaluations of the risk according to 3 risk-levels: 'low', 'medium' or 'high'. OEMs can perform their own estimations for these risks based on their knowledge of the suppliers' operations, as well as during the supplier development programs, which are already common practice ahead of new aircraft programs [Airbus, 2018]. As seen in Figure 2.4, if there were no constraints associated to supplier risk, the algorithm simply seeks to select the minimum number of suppliers, each of them delivering the largest possible number of integrated parts. While this may be the desired outcome for a risk neutral decision maker, this solution presents the greatest possible density of risk at each supplier module. Therefore, a limit is imposed on the IR within each module.

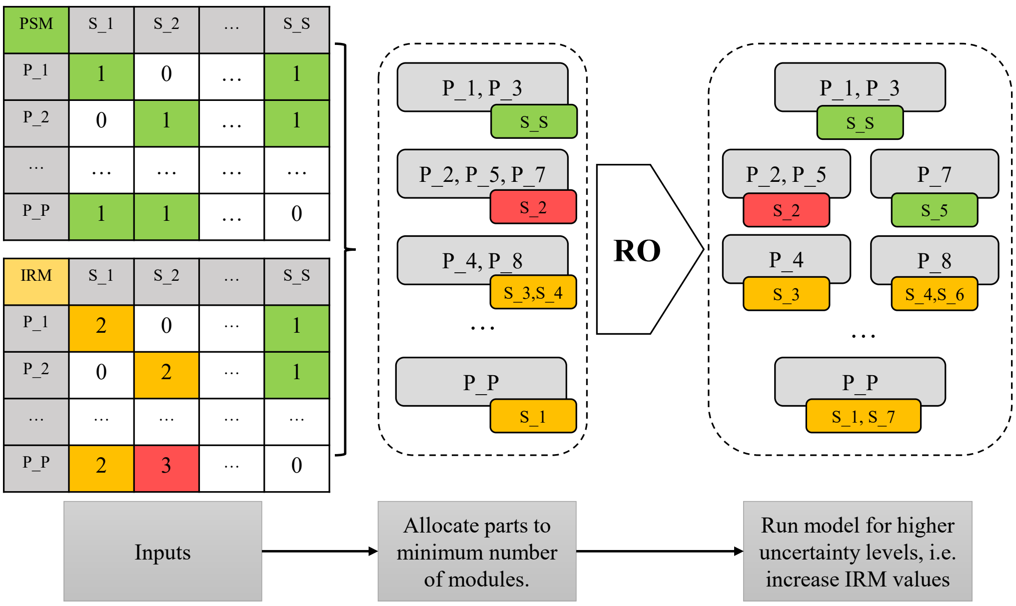


Figure 2.4: Robust CP-SCD model under supplier integration risk.

To further test the resilience of the solutions proposed by the model, we build on the work by Bertsimas et al. Bertsimas and Sim [2004] and Alem et al. Alem et al. [2018] on RO. RO is used to investigate possible mitigation strategies of the modules' integration risk. As part of this methodology, the values in the IRM are increased by an uncertain parameter. These parameters become iteratively larger, and their impact on the suggested SCD is recorded. This simulates the decision makers level of conservativeness by admitting that some values in the IRM may have been underestimated. The right-hand side of Figure 2.4 illustrates how increasing levels of risk may stand to affect the size of supplier modules, as well as the selected sourcing flexibility. SCDs produced through higher uncertainty levels represent more pessimistic scenarios, meaning that the suppliers' performance deviated considerably from the original assessment.

3 .3 Supply Chain Sustainability Performance Assessment Model: Hybrid Simulation Models

Given the supply chain structure defined at the framework level 2, the performance assessment model intends to evaluate the impact on the supply chain sustainability of the different manufacturing processes/advanced materials being considered within the IAMAT project. Following the TBL approach, different supply chain sustainability metrics, including CO_2 emissions, energy use, supply chain costs, and workload are used for a trade-off assessment.

Building on the idea proposed by Schieritz and Größler [2013], each supply chain actor is modelled as an agent. Agents locations are real and positioned in a GIS map. A GIS map allows extracting important information, as the distance between the agents, during the model run time. Additionally, the transportation modes (ship, airplane, truck) between the supply chain actors have also been modelled as agents. The internal behaviour of the transportation modes is defined by a state-chart, while the internal behaviour of the supply chain actors depends on their role.

The model was built considering the perspective of a tier 1 aerospace supplier, servicing directly the OEM. System Dynamics (SD) and business rules are used to represent the manufacturers structure of inventory and manufacturing. Also, DES is used for simulating the transport of materials between the supply chain agents, the transfer of material between transport modes at the airports and seaports, and the delay for obtaining the materials at the suppliers. The overall model structure is represented in Figure 2.5.

Five agent types can be identified in the model: customer, manufacturer, supplier, material transfer points, and transportation resources. The customer agent, the OEM, is responsible for setting the demand in the model, placing orders to the manufacturer and receiving the modules supplied by the manufacturer (tier 1 supplier). Internally, the manufacturer has the most complex structure. The manufacturers behaviour is given by the intertwined action of a SD model and business rules. While the implemented business rules are used for establishing when and how much to order materials, the SD model, an adapted version of the model proposed by Sterman [2000], for the policy structure of inventory and production, allows simulating the production activities, and the use of materials in stock. The flow rates in the SD model and the quantity of materials used to obtain the final components depend on

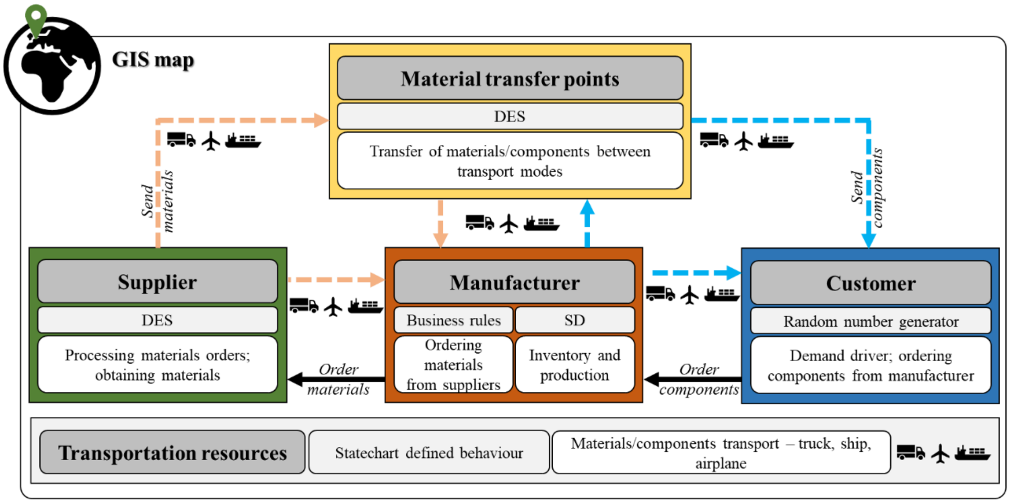


Figure 2.5: Hybrid supply chain simulation model structure.

the type of manufacturing process being considered. Within the manufacturer agent, there is a DES transportation module used to send components and receive materials.

The material transfer points correspond to the airports and sea ports where materials and final products are transferred between transportation resources. Finally, the transportation resources, that exist inside the suppliers, manufacturer, seaports, and airports, can present five internal states: when are not being used, at their owner, when loading the materials/components, going to the target location, unloading the materials/components, and returning to their owner. Each type of transportation resource has different associated monetary cost and environmental impact.

3 .4 Mixed Integer Programming Models in Sustainable Supply Chains

The SCD and planning optimisation referred to in Figure 2.2 claims for mathematical models that can integrate the three dimensions of sustainability in the supply chain. We focus now our attention in the solution techniques for model-based quantitative research, and more precisely, in MIP models addressing sustainability in supply chain.

Recently, some efforts have been made in this direction. However, quantitative modelling based approaches are still rare, as stressed in Seuring [2013]. The author presented a comprehensive survey in this topic, and concluded that the environmental dimension plays a major role and the social dimension is often neglected. This can be explained by the challenging process of modelling this component. The integration of the three dimensions of the sustainability (economic, environmental and social) was also rare since, on that date, only two contributions integrated the three dimensions of sustainability. The author pointed out that the integration of social dimension with both the economic and environmental dimensions as a future research direction.

Some efforts were done to tackle this gap. A multi-objective mixed integer linear programming model for the design and planning of sustainable supply chains is addressed in Mota et al. [2015]. This model integrates the three dimensions of sustainability. The economic dimension is assessed through the investment, salaries, acquisition, production, transportation, storage and disposal costs. The environmental impact is addressed using the life cycle impact assessment method ReCiPe 2008 [Goedkoop et al., 2009]. As stated by the authors, this methodology is not widely used in supply chain optimisation. The social dimension is assessed through the number of jobs created in less developed regions, namely the less populated regions.

A multi-objective mixed integer linear programming model approach for sustainable supply chain management is also addressed in Mota et al. [2018]. Different technology constraints are also considered, including capacity and installation constraints. The social performance is assessed taking into account the gross domestic product combined with the number of created jobs.

In the scope of the integrated framework, the hybrid simulation models can provide a set of inputs to the MIP model such as the environmental metrics of these processes, among other parameters. Additionally, uncertainty can be embedded to evaluate the impact of different scenarios. For instance, demand uncertainty, delays or non-compliance with some orders may be considered in a scenario analysis.

On the other hand, the computational time spent solving this type of MIP models tends to be very large. Therefore, efficient solution methods are mandatory to achieve good quality solutions in a reasonable computational time. Some of those methods include exact algorithms, meta-heuristic approaches or hybridisation of both methods. Besides the use of solution methods, some reformulations of the original model can reduce the computational time within the use of a commercial solver. Figure 6 depicts the methodology in the MIP development.

Using the MIP multi-objective model for supply chain design and planning in Mota et al. [2015] as a starting point, changes adopted include the replacement of some decision variables, the exclusion of some non-effective constraints and other actions that strengthen the model. Besides the real-world context of the case study, the contribution of this type of reformulations is clear, leading to stronger models that are able to provide solutions in acceptable computational time.

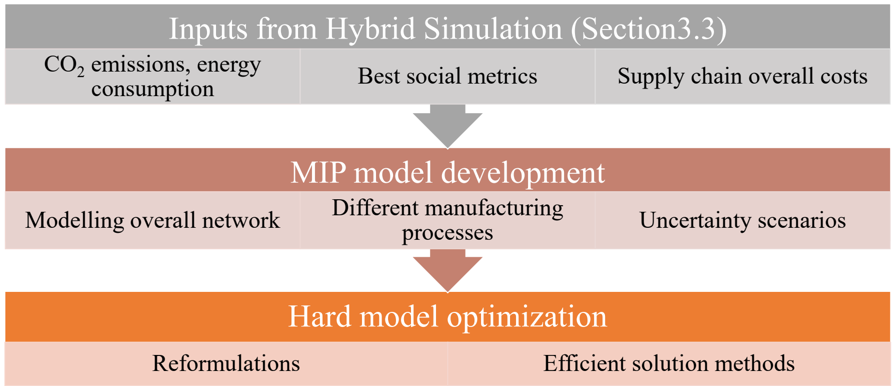


Figure 2.6: MIP model development methodology.

4 Conclusion

In this paper, we address an integrated framework for the overall aerospace supply chain in order to ensure sustainability, flexibility, resilience, and robustness. The focus is given to the development of a sustainable supply chain that enhances the introduction of new materials/manufacturing processes or new industry requirements.

A competitive decision tool to understand the evolution and new trends of aerospace supply chains is developed, along with a multimethodology for identifying and characterising stakeholders, and mapping the connections between them and their engagement and priorities towards sustainability. The CP-SCD model will yield a set of policies for resilient and robust supply chains combining efficient allocation of resources with risk management to define the modularity level of aircraft components and allocate modules to suppliers. The hybrid simulation performance assessment tool aids in the new material/manufacturing process selection through a trade-off analysis between different sustainability metrics. These metrics are used as input for the MIP model. Some reformulations and high efficient methods are used in order to achieve good solutions in a reasonable computational time.

The proposed framework provides a cross-functional decision support system that is able to assist decision makers in the development of various dimensions of the supply chain design and planning for new aircraft programs.

As new trends in the aerospace industry emerge, the framework must evolve to consider new scenarios and uncertainty contexts. This will keep the proposed approach updated and adaptable for both OEMs and suppliers.

Bibliography

Airbus. Be an airbus supplier. http://www.airbus.com/be-an-airbus-supplier.html, 2018. Accessed: 22/2/2018.

Douglas Alem, Eduardo Curcio, Pedro Amorim, and Bernardo Almada-Lobo. A computational study of the general lot-sizing and scheduling model under demand uncertainty via robust and stochastic approaches. *Computers & Operations Research*, 90:125–141, 2018.

Wouter WA Beelaerts van Blokland, SC Santema, and Ricky Curran. Lean supply chain management in aerospace. *Encyclopedia of Aerospace Engineering*, 2010.

Dimitris Bertsimas and Melvyn Sim. The price of robustness. *Operations Research*, 52(1): 35–53, 2004.

Bombardier. Stakeholder engagement, 2018.

Thiam Gan, Moritz Steffan, Martin Grunow, and Renzo Akkerman. Concurrent design of product and supply chain architectures: Method and application for modularity and flexibility. 2017.

Mark Goedkoop, Reinout Heijungs, Mark Huijbregts, An De Schryver, Jaap Struijs, and Rosalie Van Zelm. Recipe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*, 1, 2009.

IATA. Iata technology roadmap. 2013.

ICF. *Global Aerospace Sector M&A update*. Catalyst Corporate Finance, 2012.

Daniela Mocenco. Supply chain features of the aerospace industry particular case airbus and boeing. *Scientific Bulletin–Economic Sciences*, 14(2):17–25, 2015.

Bruna Mota, Maria Isabel Gomes, Ana Carvalho, and Ana Paula Barbosa-Póvoa. Towards supply chain sustainability: economic, environmental and social design and planning. *Journal of Cleaner Production*, 105:14 – 27, 2015. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2014.07.052. URL http://www.sciencedirect.com/science/article/pii/S0959652614007719.

Bruna Mota, Maria Isabel Gomes, Ana Carvalho, and Ana Paula Barbosa-Póvoa. Sustainable supply chains: An integrated modeling approach under uncertainty. *Omega*, 77:32 – 57, 2018. ISSN 0305-0483. doi: https://doi.org/10.1016/j.omega.2017.05.006. URL http://www.sciencedirect.com/science/article/pii/S0305048317304401.

Oliver Wyman. *Challenges for European aerospace suppliers*. Oliver Wyman, 2015.

Darcie Renn. Aerospace & defense. Technical report, San Francisco, CA, 2015.

Roland Berger. Aerospace industry: turning point ahead?, 2016.

N. Schieritz and A. Größler. Emergent structures in supply chains - a study integrating agent-based and system dynamics modeling. *Proceedings of the 36th Annual Hawaii International Conference on System Sciences*, 2013.

Stefan Seuring. A review of modeling approaches for sustainable supply chain management. *Decision support systems*, 54(4):1513–1520, 2013.

Rebecca Slayton and Graham Spinardi. Radical innovation in scaling up: Boeing's dreamliner and the challenge of socio-technical transitions. *Technovation*, 47:47–58, 2016.

J. D. Sterman. Business dynamics: systems thinking and modeling for a complex world. 2000.

Christopher Tang, Brian Yeh, and Joshua Zimmerman. Boeing's 787 dreamliner: A dream or a nightmare? https://tinyurl.com/2f4fytv9, 2013.

Christopher S Tang, Joshua D Zimmerman, and James I Nelson. Managing new product development and supply chain risks: The boeing 787 case. *Supply Chain Forum: An International Journal*, 10(2):74–86, 2009.

United Nations. *Supply Chain Sustainability - A Practical Guide for Continuous Improvement - Second Edition*. United Nations, 2015.

Chapter 3

Concurrent Product and Supply Chain Design Model with Integration Risk Management

Robust Supply Chain Design with Suppliers as System Integrators: an Aerospace Case Study

Nuno Falcão e Cunha[*†] · **Thiam-Soon Gan**[‡] · **Eduardo Curcio**[*] · **Pedro Amorim**[*†] · **Bernardo Almada-Lobo**[*†] · **Martin Grunow**[‡]

Submitted to *IJPR*

OEMs (Original Equipment Manufacturer) have sought new supply chain paradigms that allowed them to focus on core activities, i.e. overall product design and commercialisation. This pursuit led to partnerships with a new generation of tier-1 strategic suppliers acting as integrators. Integrators are not only responsible for system supply, but also for system design. However, critical integrators were not able to live up to their new roles, which led to costly delays in development and production. These failures highlight the ineptitude of current risk management practices employed by OEMs. To support OEMs in implementing a more differentiated and suitable approach to the use of integrators, this paper proposes a mathematical programming model for SCD (Supply Chain Design). Instead of looking at the introduction of integrators as a dichotomous decision, the model suggests the optimal number of integrators, i.e. systems, and individual part suppliers. We propose new measures for integration risk, which build upon current risk assessment practices. Robust optimisation is used to study the effect of uncertainty over baseline risk values. All approaches were tested using both randomly generated instances and real data from a large European OEM in the aerospace industry.

Keywords: Aerospace Industry · Sourcing Flexibility · Supply Chain Design · Robust Optimisation · Supply Chain Risk Management

---

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal
‡ Technical University of Munich, Chair of Production and Supply Chain Management

1 Introduction

High-tech industries with convergent supply chains have suffered heavily due to failures of critical system suppliers - i.e., integrators. For example, Boeing's attempt to partner with single source system suppliers in the 787 aircraft program resulted in almost four years of delay and billions of dollars in losses [Gates, 2015]. Tesla's Model 3 encountered production delays due to delivery stoppages from its battery system supplier, resulting in losses of more than a billion dollars, while also damaging the trust from its investors and customers [Hull, 2017]. Apple also faced delivery delays with the iPhone X from its system supplier Foxconn due to a mixture of production and supply chain issues [Wu et al., 2017].

These incidents have been caused by a new supply chain paradigm of OEMs focusing on core competencies and outsourcing sub-system design and supply to a small set of suppliers. In this context, specialised suppliers are expected to deliver fully integrated systems to the final assembly site. This relieves OEMs from managing and coordinating lower-tier suppliers.

Tang et al. [2009] identify the main hurdles in making a complete transition towards this supply chain paradigm. First, there is the suppliers' inexperience in designing and integrating components combining a wide range of technologies. Second, the OEM relies on a perfect coordination between specifications, operations and the management of each integrator. Tang et al. [2009] also provide evidence that OEMs adopt the new paradigm lacking proactive SCRM (Supply Chain Risk Management). Specifically, a concurrent PD (Product Design), supplier selection and risk assessment strategy is lacking. Traditional SCR (Supply Chain Risk) types (such as supplier reliability, quality and capacity) used do not adequately address the transition of system suppliers now responsible for successful integration.

This work identifies a new risk type, integration risk, which measures the risk of combining multiple parts in sub-systems. An exploratory stance is adopted to model this SCR employing three distinct approaches for measuring and mitigating this risk across the supply chain. We impose risk thresholds across the entire supply chain, at each supply module, or for individual part-supplier associations. The characteristics of the three approaches make it possible to adapt the model to different supply chain contexts and objectives.

Sourcing flexibility can be used as a mechanism to mitigate integration risk. Ho et al. [2015] show that double sourcing reduces supply-related risks substantially. However, for manufacturers of safety relevant products, such as medical devices, automobiles and aircraft, having alternative suppliers (sourcing flexibility) requires additional effort. Suppliers require the needed certification. Nevertheless, the choice between single and double sourcing represents a trade-off between supply chain complexity and risk exposure.

There is a need to support decision makers in addressing the complex task of integrating PD, supplier selection, and risk assessment. We develop a mathematical programming model for concurrent product system modularity - PD - and supplier selection with selective sourcing flexibility - SCD. The model minimises the number of supply modules by assigning sets of parts to one or two suppliers considering the technologies required by the parts. However, OEMs have limited insights into suppliers' integration capabilities. Hence, we use uncertain parameters to model each supplier's proficiency with the technical aspects in manufacturing and assembling the allocated parts, as well as their ability to independently manage their own supply chain. Since, for the new product, statistical distributions for the integration risk are not available, we use RO (Robust Optimisation) to test the effect of uncertainty on the concurrent PD and SCD decisions. Here, the budget of uncertainty reflects the OEMs attitude towards the integration risk. Overall, the present work is organised around three core objectives.

The first objective is to contribute to SCR literature by formalising a new risk source. The integration risk consolidates the descriptive work of Tang and Tomlin [2008], which outlines the potential supplier disruptions associated with increased systems design and integration responsibilities. We introduce a 3-level measurement scale for this risk, mirroring current practices. We propose three approaches to mitigate integration risk. These impose risk thresholds across the entire supply chain, at each supply node, or for each part-supplier association.

The second objective is to introduce a robust model that enables the concurrent application of PD, SCD and SCRM. Our model extends the deterministic work from Gan and Grunow [2016] and Gan et al. [2021], which make part integration and horizontal supply chain consolidation decisions. Our approach derives the supply modules and sourcing flexibility based on integration risk exposure targets under uncertainty.

The third objective is to quantify the trade-off between integration risk exposure and supply chain complexity, i.e., the number of modules and suppliers. We study the influence of uncertainty on PD and SCD decisions using a case study from a large European OEM in the aerospace industry, and also using randomly generated instances.

The remainder of this paper is structured as follows. Section 2 reviews relevant contributions in PD, SCD, and SCRM. Section 3 presents a deterministic mathematical programming formulation for concurrent decisions on product system modularity, sourcing flexibility, and supplier selection. We develop a robust optimisation extension to handle uncertain supplier capabilities. It further introduces different measures for the integration risk. Section 4 includes tests on both a real aerospace case study and on randomly generated instances. This section also discusses the results, managerial implications and challenges for the aerospace industry. Section 4 .2 concludes the paper.

2 Literature Review

Introducing a new product demands a clear SCD strategy. Garcia and You [2015] and Calleja et al. [2018] provide comprehensive insight into the state of the art for SCD. Their work highlights the historical trend of having the NPD (New Product Development) process preceding SCD decisions. Exploring the interaction between NPD and SCD, Graves and Willems [2005] and Amini and Li [2011] explore how OEMs should configure their supply chains to maximise new product diffusion. An emerging extension to SCD is the cross-disciplinary research on concurrent PD and SCD. Pashaei and Olhager [2015] and Gan and Grunow [2016] review the interface between these fields and identify design attributes of both fields and methodologies suitable for integrated decision making. At the architectural level, previous work simultaneously decides on product modularity along the PD-dimension and supplier selection along the SCD-dimension. However, the risks originating from making suppliers responsible for large modules have been treated in a simple way by forcing double sourcing across all modules.

Klibi et al. [2010] review SCD literature and highlight the need for focused risk sources, adapted to specific design context. Furthermore, the authors claim that this field lacks in non-value-based models, with objective functions that don't focus on minimising costs. There is also a specific mention on the need to apply RO to this field, especially with a model that does not maximise expected value. They also mention that current research does not sufficiently tackle risk mitigation constructs as design decisions. Our work makes contributions on all of these fronts.

Graves and Tomlin [2003] and Tomlin [2006] suggest that having a flexible supply base increases resiliency towards supply chain inefficiencies. Thus, SCRs can be mitigated by increasing supply chain flexibility [Yang and Yang, 2010, Chiu et al., 2011, Talluri et al., 2013, Sreedevi and Saranga, 2017], i.e., increase the number of supply sources for each part. Ho et al. [2015] highlight that dual-sourcing outperforms single-sourcing in the presence of a supply disruption [Yu et al., 2009, Li et al., 2010, Xanthopoulos et al., 2012]. Tang and Tomlin [2008] argue that even limited flexibility is sufficient to reduce process risks with other researchers indicating that using more than two suppliers brings marginal benefits [Fang et al., 2013]. Our model adjusts the sourcing flexibility to the risks resulting from the product modularity.

Although there is extensive literature about SCR [Hong et al., 2018, Hamdi et al., 2018], Ho et al. [2015] point out that past definitions are too specific to supply chain functions and do not cover the entire supply chain. Traditional risks that are considered include: demand risk (including lead time), logistics risk, supplier risk, manufacturing risk, supply risk, infrastructural risk. These risks are defined as disruptions that can be directly associated with each company's activities. For example, Li and Amini [2012] propose a SCD model for new product diffusion, with demand risk.

We formalise a new SCR, the integration risk, which does not only consider individual part conformity or delays, but also the technical and managerial capabilities of suppliers. This risk type builds on the descriptive analysis of Tang et al. [2009]. Research such as Artzner et al. [1999] provide guidelines on how to measure risk, however, to potentiate seamless industrial application for our tools, we chose to mimic current measurement practices from a large European OEM in the aerospace industry.

In general, SCD methods that consider SCR use fuzzy or stochastic programming in the form mathematical and simulation models [Sabouhi et al., 2018, Jabbarzadeh et al., 2018]. Other alternatives to deal with uncertainty, which leverage stochastic programming, were Rockafellar [2007], such as value-at-risk or conditional-value-at-risk approaches. When deciding about the modularity of new products, information on probability densities required for tackling risk with such approaches is unavailable due to lack of historical data. Bertsimas and Sim [2004] proposed RO as an alternative approach to deal with uncertainty. Uncertain parameters are characterised by a simple set of potential values. While previous work applied this concept to SCD (e.g. Hahn and Kuhn [2012]), we use RO for merging SCD with PD and SCRM.

3 Problem Statement and Mathematical Formulation

Building on the work of Gan et al. [2021], we introduce a problem that seeks an efficient and robust supply base with minimum number of product system modules, while considering the suppliers' integration risk. This decision is carried out during the planning stage for both product and supply chain. The model makes simultaneous decisions on the integration of parts into components and their assignment to a systems integrator supplier, in a module. For industries such as aerospace, demand is disregarded as a risk source at this stage.

Modules may have up to two suppliers and any number of parts. Suppliers are responsible for the design, production and pre-assembly of all parts in their module. The problem is to determine supply modules containing a set of parts and the suppliers that source them. Let $p \in P$ be the parts to be sourced and $s, i, j \in S$ the supplier candidates (see Appendix A .1 for all the relevant notation used in this paper). Modules can be single or double sourced. Supply modules are built under the following assumptions:

1. Suppliers in each supply module integrate all parts assigned to them.
2. All parts $p \in P$ can be integrated together into a larger system.
3. Each supplier can only contribute to one module, but the same module may have up to two suppliers.

Assumptions (1) is self-explanatory and embodies the main goal of supply chain integration. Assumption (2) is a simplification to the problem by ignoring the physical compatibility between parts and enhancing the model's focus on part-supplier interactions. This assumption will prioritise SCD considerations over detailed PD insight. Gan et al. [2021] circumvents this limitation by defining a design structure matrix containing compatibility parameters for each part pair. Assumption (3) was made so both design and risk decisions for each supplier are directly linked to the supply chain's modularity.

The main input in this problem is the pool of supplier candidates, represented in a PSM (Part-Supplier Matrix). The PSM contains a binary relation between parts and suppliers, and indicates whether a part can be sourced from each potential supplier.

The two main binary decision variables are $x_{(i,j)}$ and $y_{(p,s)}$. $x_{(i,j)}$ decides if suppliers i and j are in the same supply module. To allow the application of these decision variables to both single and double sourcing, a virtual supplier with index 0 is also defined. For any supplier i, if $x_{(0,i)} = 1$, supplier i is in a single sourced module. Each module has an associated parameter $h_{i,j}$ which is equal to 0 if $i = 0$, meaning that the module is single sourced, and equal to 1 otherwise. To avoid redundancy and break symmetry, we define set S' with all possible (i, j) associations such that $j > i$. $y_{(p,s)}$ decides whether a part p is sourced from supplier s. Each part may be sourced from a maximum of two suppliers.

Beyond the incorporation of risk and uncertainty described along this section, another major improvement to the work of Gan et al. [2021] was the improved computational efficiency of the deterministic model. This was achieved by reducing the size of $x_{(i,j)}$ and $y_{(p,s)}$ to not consider (i, j) and (p,s) pairs that would be invalid from the onset, based on the information from the PSM (see Table 3.1 for details on how the number of decision variables decreases in our formulation).

3 .1 Deterministic base model

Objective function (3.1) of the model is to achieve an optimal level of supplier integration by minimising the number of supply modules selected for sourcing the full range of parts. This goal represents the OEM's focus on reducing transaction costs through modularisation of its products and supply chain. An additional term with weight of α is used to break the symmetry between solutions with the same number of modules, but different sourcing flexibility. Choosing small values for α [1] maintains the priority for integration while including a preference for single sourcing and reduced management effort.

$$\min \sum_{(i,j)\in S'} [1 + \alpha \cdot h_{(i,j)}] \cdot x_{(i,j)} \tag{3.1}$$

[1] Later in our computational experiments we use a small value of $\alpha = 0.01$ as a tie breaker between our two objectives, but as a way to maintain minimising the number of modules as our main goal.

As mentioned above, decision variables $x_{(i,j)}$ and $y_{(p,s)}$ are binary:

$$x_{(i,j)} \in \{0,1\}, y_{(p,s)} \in \{0,1\} \tag{3.2}$$

Constraints (3.3) ensure that suppliers can only be in one module. Note that the virtual supplier 0 is not a part of set S and can be in multiple modules.

$$\sum_{(i,j)\in S'} x_{(i,j)} + \sum_{(j,i)\in S'} x_{(j,i)} \leq 1, \forall i \in S \tag{3.3}$$

Constraints (3.4) and (3.5) ensure that all parts must be assigned to at least one supplier, and a maximum of two. As mentioned in our literature review, building on the insight of Tang and Tomlin [2008] and Fang et al. [2013], sourcing flexibility is limited to two suppliers per module. However, despite the documented benefits of double sourcing, the model's objective is to select the least complex solution, both in number of modules and number of suppliers.

$$\sum_{(p,s)\in PS'} y_{(p,s)} \geq 1, \forall p \in P \tag{3.4}$$

$$\sum_{(p,s)\in PS'} y_{(p,s)} \leq 2, \forall p \in P \tag{3.5}$$

Constraints (3.6) activate decision variables $x_{(i,j)}$, ensuring that suppliers sourcing parts are assigned to a module. Where the set PS' contains the part-supplier allocations allowed by the PSM.

$$y_{(p,i)} \leq \sum_{(i,j)\in S'} x_{(i,j)} + \sum_{(j,i)\in S'} x_{(j,i)}, \forall (p,i) \in PS' \tag{3.6}$$

Constraints (3.7) and (3.8) relate decision variables $y_{(p,s)}$ and $x_{(i,j)}$, ensuring that if a given part is sourced from more than one supplier, those suppliers must be in the same module. The set $APSS'$ defined below contains parts that can be integrated by both suppliers, where $P'(i)$ is the set of parts that can be integrated by supplier i.

$$y_{(p,i)} \leq y_{(p,j)} + (1 - x_{(i,j)}), \forall (p,i,j) \in APSS' \tag{3.7}$$

$$y_{(p,j)} \leq y_{(p,i)} + (1 - x_{(i,j)}), \forall (p,i,j) \in APSS' \tag{3.8}$$

$$APSS' = \{(p,i,j) | (i,j) \in S', (p,i) \in PS' : p \in P'(j)\}$$

These constraints are not sufficient since they ignore parts that can be sourced from one supplier in the module, but not the other. The set $NPSS'$ lists parts that suppliers cannot integrate together. Therefore, if suppliers in this list are in the same module then neither can supply those parts, as defined in constraints (3.9) and (3.10).

$$y_{(p,i)} \leq 1 - x_{(i,j)}, \forall (p,i,j) \in NPSS' \tag{3.9}$$

$$y_{(p,i)} \leq 1 - x_{(j,i)}, \forall (p,i,j) \in NPSS' \tag{3.10}$$

$$NPSS' = \{(p,i,j) | (i,j) \in S', (p,i) \in PS' : p \notin P'(j)\}$$

Constraints (3.11) serve the opposite purpose, ensuring that suppliers that are not in the same module may not integrate the same parts.

$$y_{(p,i)} + y_{(p,j)} \leq 1 + x_{(i,j)}, \forall (p,i,j) \in APSS' \tag{3.11}$$

To improve the efficiency of the model, two sets of constraints are introduced to represent corollaries of previous assumptions. These constraints are not necessary but they correspond to valid inequalities that squeeze the solution space. Firstly, constraints (3.12) and (3.13) ensure that if a supplier sources zero parts it cannot be in a module and, if it is in a module, then it must produce at least one part.

$$\sum_{(p,i) \in PS'} y_{(p,i)} \geq \sum_{(i,j) \in S'} x_{(i,j)}, \forall (i,j) \in S' \tag{3.12}$$

$$\sum_{(p,j) \in PS'} y_{(p,j)} \geq \sum_{(i,j) \in S'} x_{(i,j)}, \forall (i,j) \in S' \tag{3.13}$$

Additionally, using only the overlapping parts of each pair (i,j) in the set $APSS'$, if $x_{(i,j)} = 1$, then suppliers (i,j) must source at least one part from this list, as defined in constraints (3.14) and (3.15).

$$\sum_{(p,i,j) \in APSS'} y_{(p,i)} \geq x_{(i,j)}, \forall (i,j) \in S' \tag{3.14}$$

$$\sum_{(p,i,j) \in APSS'} y_{(p,j)} \geq x_{(i,j)}, \forall (i,j) \in S' \tag{3.15}$$

3 .2 Incorporating Risk Measures

To incorporate a risk aversion component into the model, the IRM (Integration Risk Matrix) is introduced containing an integration risk score for each part-supplier pair (p,s). Integration risk, denoted as $r_{(p,s)}$ for part p from supplier s, is represented in a 3-level scale: 'low', 'medium' or 'high', which are stored as 1, 2 or 3, respectively. While this represents a narrow range for analysis, this scale was chosen to mirror current practices from OEMs in the aerospace industry. These estimations are based on their knowledge of the suppliers' technical and supply chain management capabilities.

Since the OEM's motivation is to improve supply chain integration, risk measures are imposed as restrictions on the model and are not included in the objective function. Three risk mitigation approaches are considered based on the OEM's feedback. Firstly, a limit on the *overall risk* of integration is imposed. The second approach improves the performance of the *weakest link* in modules by forbidding parts with risk above a certain threshold. Finally, the *additive approach* imposes an upper limit on the accrued risk of parts selected for each module.

By introducing these constraints, the deterministic model's objective is still to maximise integration, via the objective function, but this will happen as a trade-off with risk exposure. As can be seen in the following approaches, the model increases supply chain complexity, by increasing the number of modules and suppliers, to ensure these restrictions are met.

Overall risk budget approach

One possible approach of quantifying risk is to consider it as a proxy for the engineering and management resources that the OEM must allocate to solve issues with suppliers. Constraints (3.16) introduce a budget Ψ for dealing with integration risk that OEMs will make available for their supply chain. The lowest Ψ value will restrict the solutions to exclusively single sourced modules with 'low' risk parts. The highest value $(6 \cdot p)$ represents complete freedom, including all 'high' risk parts from double sourced modules. The model has the flexibility to use additional modules and double sourcing while simultaneously limiting the total supplier development cost.

$$\sum_{(p,s)\in PS'} r_{(p,s)} \cdot y_{(p,s)} \leq \Psi \tag{3.16}$$

Weakest Link Approach

The second alternative imposes the threshold R_w on the part with the highest integration risk in a module, i.e. the weakest link. This setting assumes that a single part's risk can compromise the entire module. Constraints (3.17) defines the upper bound on the risk of each part sourced from a supplier. As an example, if R_w is 2, for a single sourced module, only suppliers with 'low' or 'medium' risk will yield a feasible design. Notably, R_w may only vary between 0.5 and 3. Since all parts must be sourced, R_w equal to 0.5 is the minimum feasible value for sourcing ‘low’ risk parts, as the thresholds become $2 \cdot (0.5)$, which is equivalent to 1, the nominal value assigned to ‘low’ risk parts. For R_w equal to 3, all parts can be single-sourced, even high-risk parts which have a nominal risk value of 3. Higher values for R_w do not have a practical meaning in our model’s context.

Approximating the findings of Fang et al. [2013], a linear improvement in tolerance to risk exposure is assumed from single to double sourcing.

$$r_{(p,i)} \cdot y_{(p,i)} \leq R_w \cdot \sum_{(i,j)\in S'} [x_{(i,j)} \cdot (1 + h_{(i,j)})], \forall (p,i) \in PS' \tag{3.17}$$

Additive Approach

The additive approach evaluates the risk level of a module by adding individual risk contributions from each part, and controlling exposure via the threshold R_a. Constraints (3.18) limit the amount of risk assigned to a module by summing up the integration risk of all the parts sourced by each supplier in that module. Selective sourcing flexibility within modules is used as an additional risk mitigation strategy by offsetting the threshold. As before, dual-sourcing of a module also doubles the risk tolerance. Following the same principle used in the weakest link approach, the minimum feasible value of Ra for sourcing ‘low’ risk parts is 1, despite only allowing a single supplier in this configuration. Selecting two suppliers with ‘low’ risk parts would accrue a nominal risk value of 2, which would be over the threshold. The maximum meaningful value for Ra would allow the supplier that can source the most parts to integrate all of them, with ‘high’ risk scores, i.e., 3 times that number of parts.

$$\sum_{(p,i)\in PS'} r_{(p,i)} \cdot y_{(p,i)} \leq R_a \cdot \sum_{(i,j)\in S'} [x_{(i,j)} \cdot (1 + h_{(i,j)})], \forall i \in S \tag{3.18}$$

3 .3 Robust optimisation model

RO is used to immunise solutions against uncertainty. By applying RO to each risk approach, the SCD method can take into account the variability in the estimated performance of supplier candidates. Since the IRM values are estimates made by the OEM, it is possible that they may be incorrect or vary over the lifetime of the aircraft. Using robust optimisation, an uncertain dimension is associated to each value in the IRM. Take $\tilde{r}_{(p,s)}$ to be the uncertain parameter, such that $r_{(p,s)}$ is its nominal value, estimated by the OEM. Let $\bar{r}_{(p,s)}$ be its maximum deviation from the baseline estimation. $\tilde{r}_{(p,s)}$ can be written as follows: $\tilde{r}_{(p,s)} = r_{(p,s)} + \bar{r}_{(p,s)} \cdot \xi_{(p,s)}$, where $\xi_{(p,s)}$ is the scaled deviation $\xi = (\tilde{r} - r)/\bar{r}$, which takes values within the interval $[0,1]$.

For each of the three risk measures, an unique polyhedral uncertainty set is defined. Uncertainty sets U^o, $U^w_{(p,s)}$ and U^a_s define all uncertainty scenarios for the overall risk budget (o), weakest link (w) and additive (a) approaches, respectively. e represents a vector of ones with the appropriate dimensions for each uncertainty set.

$$U^o = \{\xi^o \in \mathbb{R}_+^{|PS'|} : \xi^o \in [0,e], e^T \xi^o \in [0,\Gamma]\} \tag{3.19}$$

$$U^w_{(p,s)} = \{\xi^w \in [0,1], \xi^w \in [0,\Gamma_{(p,s)}]\} \tag{3.20}$$

$$U^a_s = \{\xi^a \in \mathbb{R}_+^{|P_s|} : \xi^a \in [0,e], e^T \xi^a \in [0,\Gamma_s]\} \tag{3.21}$$

Robust optimisation increases the values $\xi_{(p,s)}$ towards the worst possible scenario. The size of the uncertainty set is defined by the Γ parameters. By varying these integration risk evaluations, it will be possible to study the impact of the uncertainty on solutions. Let Γ, $\Gamma_{p,s}$ or Γ_s be the maximum number of deviations allowed to the IRM values. The realisations produced through higher uncertainty levels represent more pessimistic scenarios, meaning that the suppliers' performance increasingly deviates from the original assessment.

Comparing this extension that considers uncertainty with the deterministic model, the goal is still to maximise integration. However, the risk thresholds become harder to uphold as Γ-values go up. Thus, it is predictable that the price of robustness will be more complexity, i.e., more modules and/or more suppliers.

Overall risk budget approach

$\tilde{r}_{ps}$ is introduced as the integration risk for each part-supplier pair under uncertainty. As such, the robust counterpart for constraints (3.16) is written in constraints (3.22). RO imposes an optimisation problem on the relevant constraints that must remain feasible for all realisations of ξ^o in the uncertainty set U^o, as described in constraints (3.23).

$$\sum_{(p,s)\in PS'} [(r_{(p,s)} + \bar{r}_{ps}\xi^o_{(p,s)}) \cdot y_{(p,s)}] \leq \Psi, \forall \xi^o \in U^o \tag{3.22}$$

$$\sum_{(p,s)\in PS'} (r_{(p,s)} \cdot y_{(p,s)} + \max_{\xi^o \in U^o} (\bar{r}_{ps} \cdot \xi^o_{ps} \cdot y_{(p,s)})) \leq \Psi \tag{3.23}$$

As shown by Bertsimas and Sim [2004] these constraints can be transformed into tractable robust counterparts. This transformation is outlined in Appendix A .2. Thus, the overall risk budget approach produces constraints (3.24) and (3.25), with the bounds on each decision variable defined in equation (3.26). $\mu_{(p,s)}$ and λ are variables used to write the robust counterpart of the risk constraints in the dual version.

$$\sum_{(p,s)\in PS'} [r_{(p,s)} \cdot y_{(p,s)}] + \left[\Gamma \cdot \lambda + \sum_{(p,s)\in PS'} \mu_{(p,s)}\right] \leq \Psi \tag{3.24}$$

$$\lambda + \mu_{(p,s)} \geq \bar{r}_{(p,s)} \cdot y_{(p,s)},\ \forall (p,s) \in PS' \tag{3.25}$$

$$\lambda,\ \mu_{(p,s)} \geq 0,\ \forall (p,s) \in PS' \tag{3.26}$$

Weakest link approach

Applying the same uncertainty parameters for r_{ps} to Constraints (3.17) yields Constraints (3.27).

$$(r_{(p,i)} + \bar{r}_{(p,i)} \cdot \Gamma_{(p,i)}) \cdot y_{(p,i)} \leq R_w \cdot \sum_{(i,j)\in S'} [x_{(i,j)} \cdot (1 + h_{(i,j)})], \forall (p,i) \in PS' \tag{3.27}$$

This formulation does not produce a RO problem. Since the Γ-values have the same dimensions as the constraints, these will not have robust counterparts. $\Gamma_{(p,s)}$ is defined for each part-supplier pair, with a maximum value of 1. Therefore, a study on the robustness of the solutions will consist of looking at snapshots of incremental deviations from the original IRM. If $\Gamma_{(p,s)}$ is the same for all pairs, then the variations are shared across original estimations of equal score. OEMs with access to historical data on suppliers' performance may assign individual $\Gamma_{(p,s)}$ to each supplier. Alternatively, unique $\bar{r}$ can be set for each part-supplier entry.

Additive approach

Re-writing Constraints (3.18) to incorporate the uncertain parameter $\tilde{r}_{(p,s)}$ and ensuring their feasibility for every value of $\xi^a_{(p,s)}$ over the uncertainty set U^a_s leads to Constraints (3.28). In the context of RO, these constraints are re-written as a new optimisation problem in Constraints (3.29).

$$\begin{gathered}\sum_{(p,i)\in PS'} \left[r_{(p,i)} + \bar{r}_{(p,i)} \cdot \xi^a_{(p,i)}\right] \cdot y_{(p,s)} \leq RHS_i, \forall \xi^a \in U^a_s \\ RHS_i := R_a \cdot \sum_{(i,j)\in S'} [x_{(i,j)} \cdot (1 + h_{(i,j)})], \forall \xi^a \in U^a_s\end{gathered} \tag{3.28}$$

$$\sum_{(p,s)\in PS'} (r_{(p,s)} \cdot y_{(p,s)} + \max_{\xi^a \in U^a_s} (\bar{r}_{ps} \cdot \xi_{ps} \cdot y_{(p,s)})) \leq RHS,\ \forall s \in S \tag{3.29}$$

Using the same transformation described in Appendix A .2, the tractable robust counterpart is obtained by incorporating the dual auxiliary problem as shown in Constraints (3.30) and (3.31). The bounds for λ_s and $\mu_{(p,s)}$ are described in Constraints (3.32). Γ_s ranges between 0 and the total number of parts that can be sourced by each supplier, i.e. it is the sum of the $\xi^a_{(p,s)}$ components for each supplier.

$$\sum_{(p,s)\in PS'} [r_{(p,s)} \cdot y_{(p,s)}] + \left[\Gamma_s \cdot \lambda_s + \sum_{(p,s)\in PS'} \mu_{(p,s)} \right] \leq RHS_i, \forall s \in S \tag{3.30}$$

$$\lambda_s + \mu_{(p,s)} \geq \bar{r}_{(p,s)} \cdot y_{(p,s)}, \ \forall (p,s) \in PS' \tag{3.31}$$

$$\lambda_s, \ \mu_{(p,s)} \geq 0, \ \forall (p,s) \in PS' \tag{3.32}$$

3 .4 Assigning probabilities to constraint violation

Traditional RO methods deal with bounded uncertainty, i.e., they assume lower and upper bounds for the uncertain parameters. Then, as outlined above, worst-case robust counterparts are derived for each constraint. The uncertainty sets are defined under the assumption that uncertain parameters can't realise values that render an optimal solution infeasible. One notable limitation has been the lack of information regarding the probabilities for the realisations of uncertain parameters. Ben-Tal and Nemirovski [2000] and Bertsimas and Sim [2004] were the first to use uncertainty sets with non-zero probabilities of constraint violation and derived *a priori* upper bounds for this probability. Models solved using this method yield less conservative solutions.

The recent studies of Guzman et al. [2016, 2017a,b] have improved these bounds and suggested the introduction of PDFs (Probability Density Function) for the sources of uncertainty. This method is valid provided the problem is based on uncertain and independent parameters, which have a known CGF (Cumulant Generating Function), and that the expected value for each density function is zero. Not only does this method stand to improve the model's solutions, it also boosts the applicability of these tools by providing decision makers with a novel way to parametrise their decisions by assigning their tolerance for the probability of violating the risk constraints. In the context of our problem, integration risk values must be replaced for each part-supplier by PDFs.

Hesse [2000] indicates that triangular distributions are best suited for scenarios where uncertain parameters are based on an “educated guess". As the IRM values used by OEMs are qualitative assessments of each supplier's expected performance, triangular distributions seem to be the best fit for this analysis. Triangular distributions are defined via the lower and upper limits, and the mode. We assume separate asymmetric right triangular distributions for part-supplier pairs in the range between $r_{(p,s)}$ and $r_{(p,s)} + \bar{r}_{(p,s)}$. An illustration of how this range can be normalised via $\xi_{(p,s)}$ is shown in Figure 3.1 (left). Since the IRM stems from the multivariate assessment of suppliers, it is also taken as the mode. The use of triangular distributions does not change the formulation of the robust counterparts.

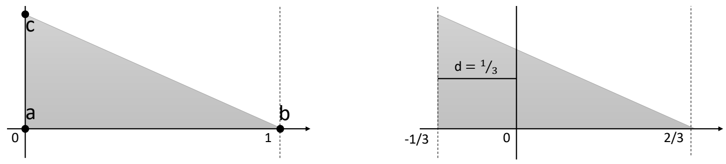


Figure 3.1: Non-symmetrical triangular distributions between 0 and 1 (left) and the necessary transformation to the range between $-1/3$ and $2/3$ via the parameter $d = 1/3$ (right). This ensures that the expected value of the distributions is zero, i.e., $a+b+c=0$.

Guzman et al. [2017a] define a theoretical bound for the probability of violation for constraints with uncertainty terms. To fit the aforementioned specifications, the distributions must be shifted by $d = 1/3$ so the expected value of the distribution is zero. New MGF (Moment Generating Function), M_{ps}, and CGF, Λ_{ij}, must be derived (see Appendix A .4). This bound is given by the inequality shown below. The extra term $d\theta$ represents the offset in the distributions.

$$Pr\left\{\sum_{(p,s)} r_{(p,s)} y_{(p,s)} + \sum_{(p,s)\in PS'} \xi_{(p,s)} \bar{r}_{(p,s)} y_{(p,s)} > R_a\right\} \leq$$
$$exp\left(\min_{\theta>0}\left\{-\theta\Gamma_a + \sum_{(p,s)\in PS'} (d\theta + \Lambda_{(p,s)}(\theta))\right\}\right)$$

Using Algorithm 1 in Guzman et al. [2017a] (see Appendix A .3), Γ-values are calculated for different probabilities of constraint violation. By limiting the deviations from the baseline, Γ-values control the trade-off between performance and probability of violating risk constraints.

4 Computational Experiments

Figure 3.2 illustrates a typical model solution in which suppliers hold integration responsibilities for larger modules and while others supply only single parts. For modules M1-M6, the model decides for double sourcing, while the remainder is only single sourced.

The computational experiments in this section analyse how the structure of the solution changes according to the three risk mitigation approaches. For the additive approach, an additional analysis on the probability of constraint violation is carried out.

The first set of tests uses data from a large European OEM in the aerospace industry. The insight from these experiments is extended using randomly generated data for the second batch of tests.

	Real OEM	**Set 1**	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**	**Set 7**
$x_{(i,j)}$	713	162	168	314	427	332	414	427
$y_{(p,s)}$	166	76	76	121	166	121	166	166
Gan et al. [2021]	82000	82000	82000	82000	82000	82000	82000	82000

Table 3.1: Number of decision variables for the deterministic SCD model with risk in comparison to the SCD model in Gan et al. [2021].

All computational experiments followed scripts implemented in OPL and were executed using the IBM ILOG CPLEX Optimization Studio 12.6.0.0 on an Intel(R) Core(TM) i7-4790 CPU @3.60GHz with 16.0Gb of RAM, under a Windows 8.1 Pro Operating System. Table 3.1 illustrates the complexity and provides insight into the practicality of this SCD model.

4 .1 Aerospace OEM Instance

In this section, the model is applied to a setting provided by a large European OEM in the aerospace industry. The data set contains one hundred available suppliers and forty-one different parts. These parts represent partially assembled components, and the model will attempt further integration. The total number of parts in an aircraft is multiple orders of magnitude greater. In the following subsections, we show results for the three different risks approaches.

Recall that the integration risk r(p,s) is represented in a 3-level scale: 'low', 'medium' or 'high', which are stored as 1, 2 or 3, respectively.

Results for the overall risk budget approach

Figure 3.3 shows the results for the overall risk budget approach for Γ values of 0 (deterministic solution), 0.05 and 0.1. The plot shows the ratio of modules to the number of parts. The lower this ratio is, the higher the integration level.

Since not all parts have 'low' risk supplier candidates, the minimum feasible Ψ is 51 (68, 84), instead of 41, for Γ = 0 (0.05, 0.1). For each uncertainty level, we observe a sharp increase in the objective function for the lowest feasible values of Ψ. Given that the maximum allowed budget Ψ for this industry setting is 246 (cut off in the figure), there is a very narrow range in Ψ that considerably decreases the integration level.

The solutions yielded by the model suggest nearly halving the number of supply nodes (21 modules/41 parts = 0.51). Further integration could be expected, were it not for the extreme specialisation found in suppliers. Among the 100 supplier candidates included in the PSM, 71 suppliers can only produce a single part. Therefore, if selected, they must be in a single-part module.

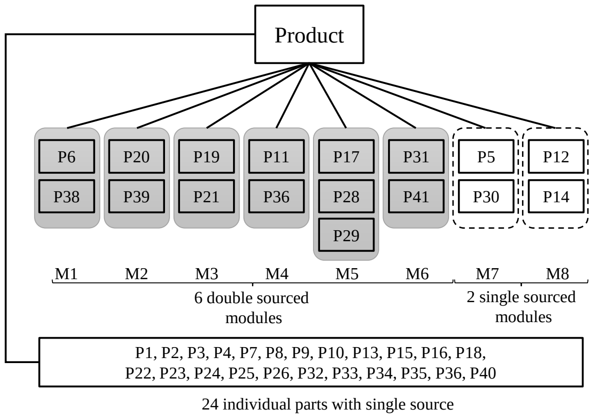


Figure 3.2: Result for case-study with aerospace OEM using the additive approach with $\Gamma_s = 0.4$. Solution yielded thirty-two modules with six double sourced modules M1-M6.

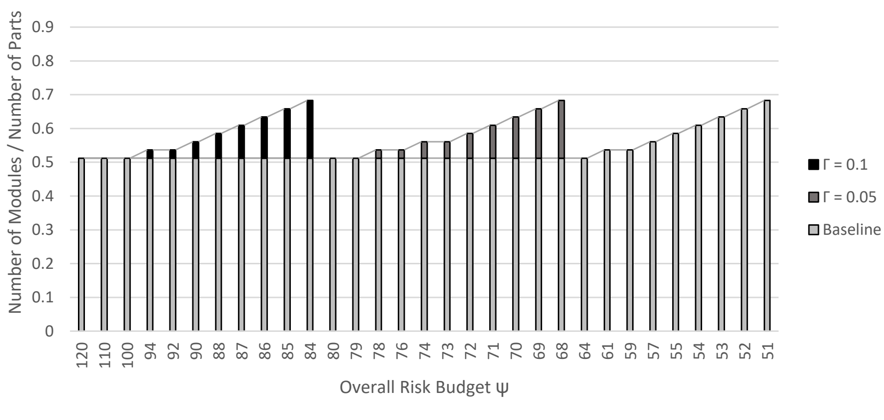


Figure 3.3: SCD solutions for case-study with aerospace OEM using the overall risk budget approach to risk management in supply modules.

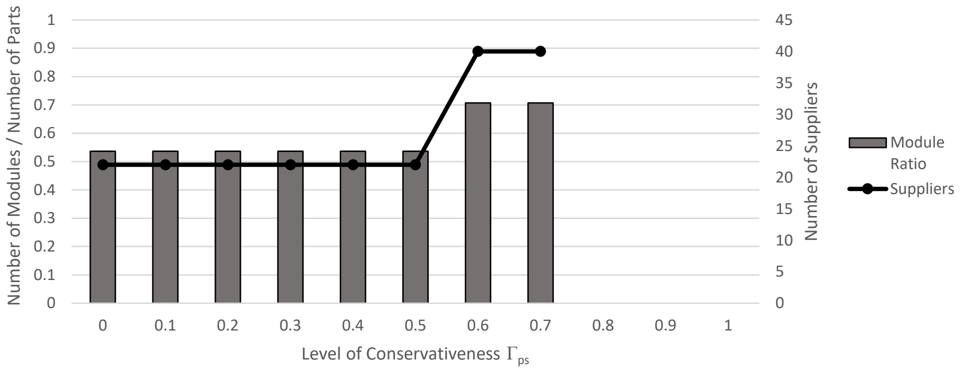


Figure 3.4: Solutions for case-study with aerospace OEM using the weakest link approach to risk management in supply modules.

Results for the weakest link approach

Figure 3.4 shows model solutions for R_w equal to 2.5. This value was chosen since it means that double sourcing is only required for 'high' risk parts. This makes it possible to observe the dynamic sourcing flexibility risk mitigation mechanism without having an overwhelming number of double sourced parts. To extend this rule for 'medium' risk parts, R_w would have to be between 1 and 2. Having R_w between 0.5 and 1 would require double sourcing for 'low' risk parts as well.

One key aspect in these results is the value of $\Gamma_{ps} = 0.6$ where the number of parts per module decreases, thus decreasing the integration level. This is accompanied by a shift towards exclusively double sourced modules. Our results show that there is a narrow range in the tolerated realisations of uncertainty that causes a transition from a solutions with full risk exposure to a solution with high degree of conservativeness.

No solution can be found beyond $\Gamma_{(p,s)} = 0.7$. The extreme specialisation of suppliers in the aerospace industry and enforcing that suppliers can only participate in one supply module, means it is infeasible to double source all parts. This means that extreme levels of conservativeness cannot be reached.

Results for the additive approach

Figure 3.5 shows the results of the additive approach for different levels of conservativeness using a $R_a = 4$. For a level of conservativeness of $\Gamma_s = 0.4$, Figure 3.2 shows the

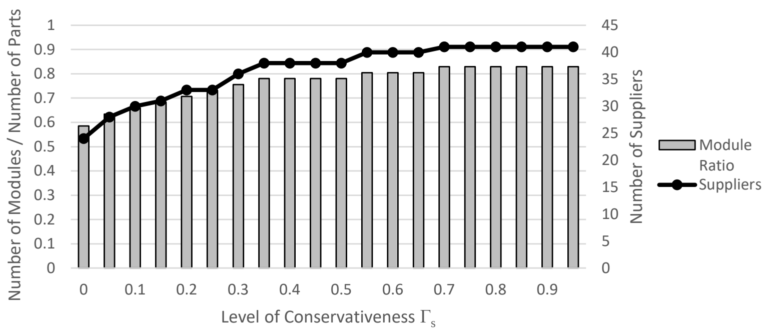


Figure 3.5: SCD solutions for case-study with aerospace OEM using the additive approach to risk management in supply modules, with $R_a = 4$.

resulting module structure and supply chain architecture. This approach achieved the least horizontal integration across all approaches, for the baseline values. For high levels of conservativeness, the model yields a module ratio of 0.83 with 41 suppliers. This translates into thirty-four modules, seven of which are double sourced. The model thus achieves a final integration of only 1.2 parts per module. As with the weakest link approach, a prevalence of highly specialised suppliers considerably limits the integration potential. However, across the entire conservativeness range, ten alternatives with varying number of modules and sourcing flexibility are obtained. As previously stated, this nuanced outcome of the additive risk measure is one of the biggest advantages off using this approach.

Using the methodology proposed by Guzman et al. [2017a], the model was solved using RO with triangular distributions for each uncertain parameter. Notably, high values of Γ_s (above 0.65) correspond to probabilities of constraint violation close to 0%, which can be observed by comparing Figures 3.5 and 3.6.

4 .2 Randomly generated instances

The randomly generated instances consider fifteen parts and thirty suppliers. Different instances were created by varying the number of available suppliers per part, and the range for the suppliers' integration risk.

The first, most constrained setting has five suppliers per part and the total integration risk for each supplier is randomly chosen from the interval between 1 and 5. Hence, each supplier can supply at least one low risk part, and at most five low risk parts (or, for example, one high risk part and one medium risk part).

For the remainder randomly generated instances, the number of suppliers per part was increased in steps of three, and the upper and lower limit of the total integration risk were also increased by three. Five unique instances were generated for each such setting. Table

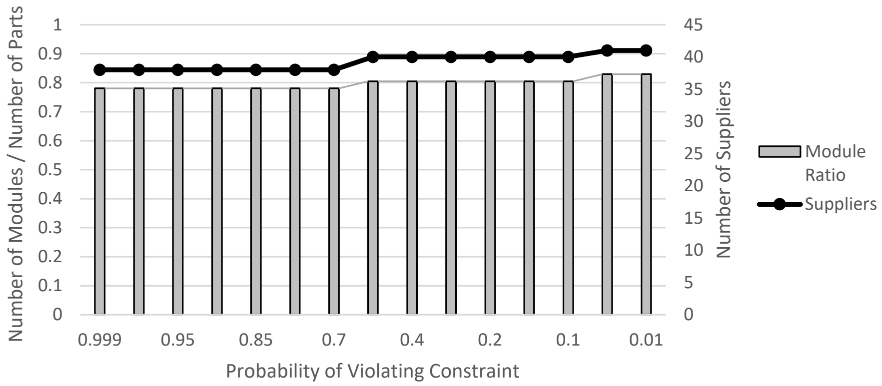


Figure 3.6: Solutions for case-study with aerospace OEM using robust optimisation with additive approach to risk management in supply modules, for varying values of probability of constraint violation.

3.2 outlines the parameters for each randomly generated instance, and the labels used for the instances in this section. For the given number of parts, the indicated combinations of parameters settings yield meaningful problem instances.[2]

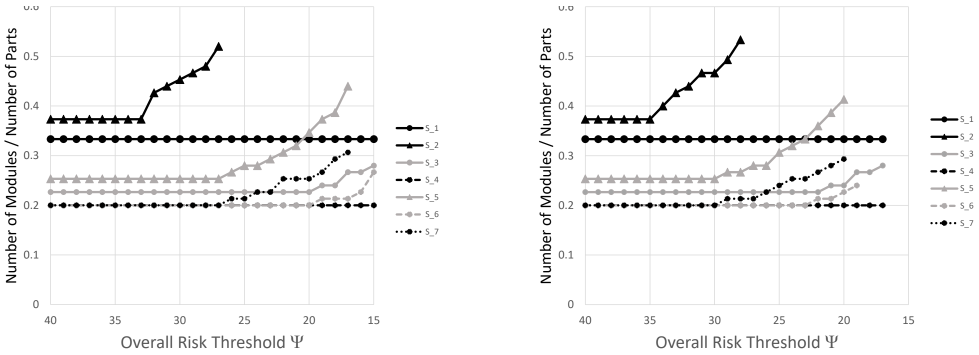
Results for overall risk budget approach

Figure 3.7 plots solutions for all randomly generated instances. For each instance set, the values for the number of modules were averaged, and the plot shows the ratio of modules to the number of parts. The lower this ratio is, the higher the integration level. Figures 3.7(a) and 3.7(b) show results for the IRM baseline values (deterministic solutions) and for 20% of the maximum Γ-value, respectively. Different solutions are presented for varying overall risk thresholds, Ψ. Notice that for tight risk thresholds no feasible solution can be found, which is why the lines discontinue for Instance Sets 2, 5, 6, and 7.

[2]Parameters for randomly generated instances can be downloaded from: Cunha, Nuno (2022), "Theoretical Instance for SCD Model", Mendeley Data, V3, doi: 10.17632/m3rrb8tpfv.3

	Risk Per Supplier			
Suppliers Per Part	**1 - 5**	**4 - 8**	**7 - 11**	**10 - 14**
5	Instance Set 1	Instance Set 2	–	–
8	–	Instance Set 3	Instance Set 5	–
11	–	Instance Set 4	Instance Set 6	Instance Set 7

Table 3.2: Design parameters for randomly generated instances.



((a)) ((b))

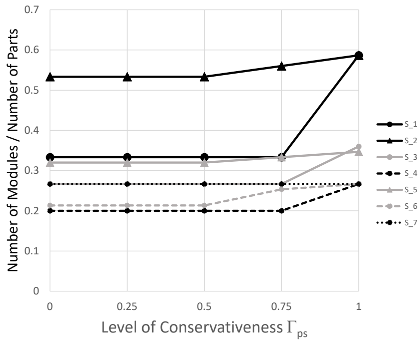
Figure 3.7: Solutions for randomly generated instances for the overall risk budget approach with **(a)** $\Gamma = 0$ and **(b)** $\Gamma = 0.2$.

The different instance sets show how having more available suppliers for each part increases the likelihood of higher integration levels (observable by comparing Instance Sets 2,3, and 4 and Instance Sets 5 and 6). Conversely, increasing the risk range per supplier leads to lower integration levels (observable by analysing Instance Sets 1 and 2, Instance Sets 3 and 5, and Instance Sets 4, 6, and 7). Since selecting two suppliers for the same part doubles the risk mitigation effort, this approach will never select double sourced modules. As outlined in Section 3 .2, for our instances, Ψ can vary between 15 and 90. However, the overall risk constraints do not restrict solutions for large values of Ψ (observable by the constant ratio of modules to the number of parts for Ψ values larger than 33 in Figure 3.7(a) and larger than 35 in Figure 3.7(b)). This pattern occurs for the different instance set at varying thresholds. In some cases, the overall risk threshold does not impose a change in the solution structure (Instance Set 1 and 4). Because of the relatively low risk associated with the suppliers in these instances, the approach results in modules with a low integration risk even without a tight risk threshold. Overall, selecting lower values of Ψ forces OEM to select new suppliers with lower risk evaluations, thus increasing the number of modules, and decreasing the integration level.

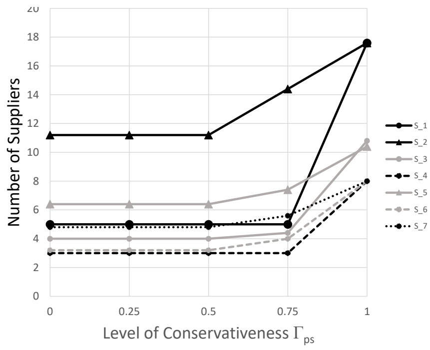
Figure 3.7(b) indicates that variations in 20% of the IRM values result in solutions that are shifted by one or two units of Ψ when compared to the baseline. Thus, if the suppliers' risk levels are uncertain, each value of Ψ will yield equal or lower integration levels, or even infeasible solutions.

Results for weakest link approach

Figures 3.8(a) and 3.8(b) show the module ratio and number of double sourced modules yielded by solutions for $R_w = 2.5$ for varying $\Gamma_{(p,s)}$ values, respectively. This means double sourcing is only required for 'high' risk parts. For every level of conservativeness $\Gamma_{(p,s)}$, the



((a))



((b))

Figure 3.8: Solutions for randomly generated instances for the weakest link approach with $R_w = 2.5$, **(a)** ratio of supply modules, **(b)** number of double sourced modules.

nominal value of $r_{(p,s)}$ has been increased by $\Gamma_{(p,s)} \cdot \bar{r}_{(p,s)}$, where $\bar{r}_{(p,s)}$ is the gap between the original risk value and its maximum, 3.

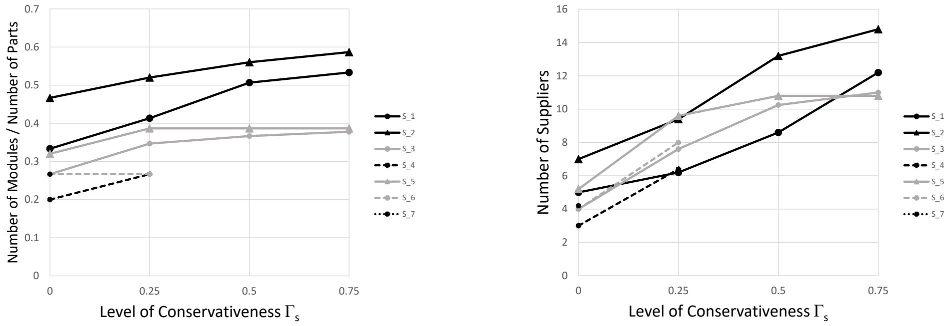
Analysing Figures 3.8(a) and 3.8(b) it is shown that an increasing level of conservativeness leads to less integration and more double sourcing. In some cases, even for baseline IRM values, the model selects double sourced modules (observable in Instance Sets 2, 5 and 7).

Based on the detailed results within each instance set, it is noticeable that the weakest link approach produces divergent solutions both in integration performance and sourcing flexibility, even for instances with equivalent design attributes. This approach analyses the risk at the level of individual part-supplier assignments. Therefore, for a given R_w, the model guarantees that all parts will be double sourced, for which there are only suppliers with IRM values larger than this risk threshold. Building modules around such double sourced parts is difficult, because it requires overlapping supplier capabilities. As a consequence, the integration level for such instances is low. Instances with more suppliers per part are more likely to have at least one 'low' IRM supplier per part, and achieve higher integration levels (observable when comparing Instance Set 4 against 2).

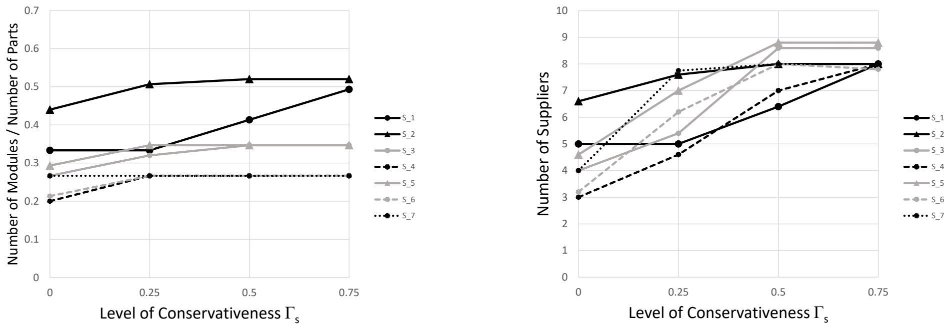
Results for additive approach

Figure 3.9 contains plots of the solution structure for all instance sets, using the additive approach. Figures 3.9(a) and 3.9(c) present the ratio of supply modules for $R_a = 5$ and $R_a = 6$, respectively. Figures 3.9(b) and 3.9(d) display the corresponding number of double sourced modules. From left to right, the level of convervativeness, Γ_s, for each supplier increases by the same percentage for each supplier. This normalisation makes it possible to track uncertainty levels across suppliers that can produce different number of parts.

Comparing the solutions in Figure 3.9, higher conservativeness levels require more supply modules, thus decreasing the integration level. As expected, the number of double



((a)) Ratio of modules $R_a = 5$ ((b)) Number of double sourced modules $R_a = 5$



((c)) Ratio of modules $R_a = 6$ ((d)) Number of double sourced modules $R_a = 6$

Figure 3.9: Solutions for randomly generated instances for additive approach with $R_a = 5$ – **(a)** ratio of supply modules, **(b)** number of suppliers – and $R_a = 6$ – **(c)** ratio of supply modules, **(d)** number of suppliers.

sourced modules also increases. Predictably, increasing the amount of risk that can be accumulated at each module to $R_a = 6$ allows for greater integration levels with less suppliers, especially for higher levels of uncertainty. In the graphs, we just report the runs for which an optimal solution can be found. For Instance Sets 4, 6 and 7 the model failed to find the optimal solution within three hours for high levels of convervativeness. This limitation does not jeopardise the previous insights.

Limits on probability of constraint violation

Similarly to the final analysis in Section 4 .1, using the methodology from Guzman et al. [2017a], we assign an asymmetric triangular PDF for each risk value in the IRM. This approach adds a layer of complexity but allows to improve the accuracy in measuring the probability of constraint violation and the applicability of RO.

We apply this methodology to the additive approach. We choose this risk measure due to the superior performance outlined above. As before, the threshold R_a and the level of uncertainty, Γ_s, represent the decision maker's risk aversion. The association of PDFs to uncertainty values allows for a more intuitive adjustment of these two aversion parameters. Rather than estimating the number of incorrect values in the IRM, Γ_s, decision makers can directly represent their risk adverseness by deciding the probability of constraint violation. A lower probability corresponds to a larger risk adverseness.

Using Algorithm 1 in Guzman et al. [2017a] (see Appendix A .3), we determined values of Γ_s for each supplier, for a given probability of constraint violation. Figure 3.10 shows the solutions for the first instance from Instance Set 3 using both methodologies. Implicitly, this methodology associates higher values of Γ_s with smaller probabilities of constraint violation.

By comparing the solution profiles it is clear that this alternative methodology [Guzman et al., 2017a] is more conservative than solving the model by iterating over Γ_s values. Indeed, the solutions for probabilities of constraint violation equal to 0.999, 0.99 and 0.95 are the same as for Γ_s equal to 0.35. Henceforth, this methodology rules out solutions with high integration level, such as the one found for Γ_s below 0.2, which correspond to four modules, but lead to an unacceptable probability of constraint violation.

On the other hand, the initial RO methodology suggests a solution with five modules, three of which double sourced, to cover most of the Γ_s range. However, the entirety of this range corresponds to a probability of constraint violation below 5%. This way, a decision maker solving exclusively for the entire range of Γ_s could overestimate the likelihood of this solution, thus hindering the integration potential and supplier effort for their supply chain.

All other instances lead to similar insights.

sectionConclusion

Post-Covid/Post-Glasgow (COP26) aerospace industry, driven by both economic and environmental factors, is presented with the opportunity to develop new types of environmentally friendly aircrafts using new design and manufacturing technologies. This situation offers aerospace OEMs opportunities to also rethink their supply chain strategically. This paper provides a timely contribution to this endeavour by providing a method to design the supply chain, while considering the risk of selecting Tier 1 suppliers based on their capabilities to hold system integration responsibilities and manage lower-tier suppliers in their supply scope.

Supporting recent practices in OEMs with convergent supply chains, this paper presents an optimisation model for concurrent PD and SCD. As companies in several industries built supply chains heavily reliant on outsourcing system design and integration responsibilities to a small set of suppliers, they were exposed to a new risk – integration risk.

This risk relates to the likelihood of disruptions associated with the increased technical and managerial capabilities demanded from key strategic suppliers that took on the role of 'integrators'. We base our approach on the industry practice of estimating supplier capabilities for individual parts. Three distinct approaches were employed to measure the effect

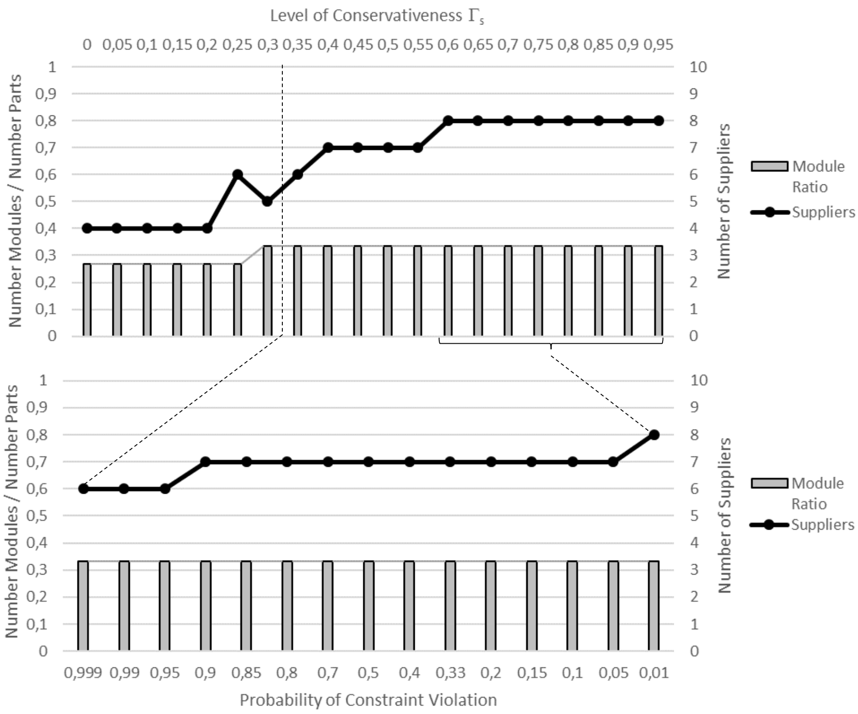


Figure 3.10: Solutions for a randomly generated instance using the additive approach for varying values of Γ_s and for different probabilities of constraint violation, for $R_a = 6$.

of integration risk in concurrent PD and SCD: overall risk budget approach, weakest link approach and additive approach. These methodologies aim to reflect supplier management and development efforts (overall risk budget), to account for the risks involved in sourcing parts with high risk scores (weakest link) and to prevent high risk exposure at individual modules (additive approach).

Our robust model optimises supply chain integration while mitigating the associated risk, yielding solutions that combine integrators with specialised suppliers. For a given supply base, we determine levels for module integration, the assignment of modules to suppliers, and the usage of double sourcing based on the risk estimations and decision-makers' levels of conservativeness. Thus, the price of robustness is decreasing horizontal integration in tandem with an increase in the number of suppliers.

To provide decision makers with a more intuitive parametrisation of the model, uncertain risk estimates were modelled as asymmetric triangular distributions. The model was tested using both randomly generated instances and real supplier data from a large European OEM in the aerospace industry.

4 .3 Managerial Insights

The insights revealed by both the real case-study and the randomly generated instances are consistent. The results showed that our modelling approach is useful in determining solutions that shape modules and select the respective level of double sourcing. Furthermore, the solutions are tailored to the individual supply base and cannot be found by a simple policy or decision rule.

Unlike the findings of other papers in the field of SCD, such as Li and Amini [2012], we do not conclude that double sourcing outperforms single sourcing, regardless of the sourced part. Instead, we consider an increase in managerial effort arising from the interface with additional partners. Thus, we only select extra suppliers if it is necessary to comply with risk exposure thresholds while achieving greater integration performance.

Thus, we show how having suppliers that can manufacture more parts will enable higher levels of integration. Similarly, having more suppliers available for each part will sustain higher risk at modules and improve integration by potentiating double sourcing. OEMs should leverage this result to invest in developing their supplier base achieving more versatile suppliers and more redundancy for each part.

Moreover, the results provide a set of guidelines for each of the proposed risk approaches to mitigate integration risk.

The overall risk budget approach is best suited for low uncertainty levels in the presence of low risk suppliers. It can not accommodate large uncertainty deviations. However, it is the only measure that represents management effort. Therefore, it presents the possibility of considering available risk management resources in the concurrent PD and SCD process.

The weakest link approach produces diverse solutions both in integration performance and sourcing flexibility, even for instances with equivalent design attributes. Building modules around high-risk, double sourced parts is difficult, because it requires overlapping supplier capabilities. As a consequence, the integration level for this measure is low. However, the weakest link approach may be suited for individual, high-risk part-supplier profiles. For example, if the OEM is considering the introduction of a new material or technology into their aircraft programmes, these constraints can be defined exclusively for those parts.

The results from applying the additive approach showed a multitude of different PD and SCD configurations for different levels of conservativeness. This approach best exploits the possibilities to module sizing and double sourcing to respond to risk adverseness. However, a comparison with solutions guided by the probability of risk violation revealed that only a limited part of the solutions should be considered.

Compared to the overall risk budget and weakest link approaches, the additive approach is more sensitive towards changes in the level of conservativeness. On one hand, the first two approaches have a sharp change in integration performance caused by specific levels of conservativeness. On the other, the additive approach provides more alternatives to decision

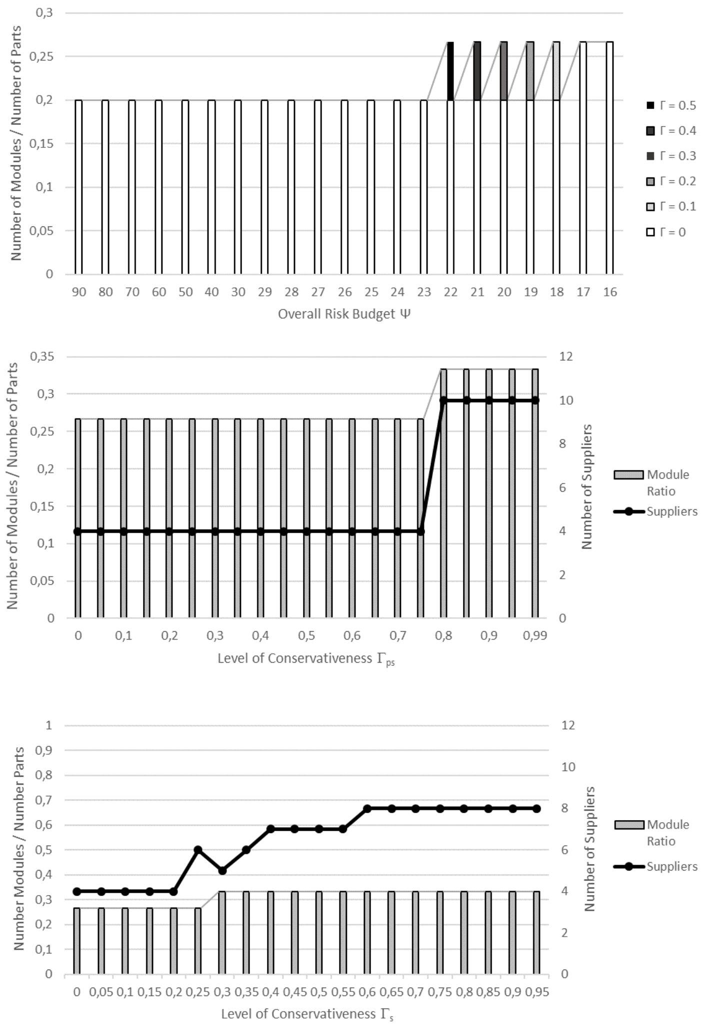


Figure 3.11: Solutions for a randomly generated instance using the overall risk budget, weakest link and additive approaches, for $R_a = 6$.

makers with distinct risk aversion profiles. This can be observed by compiling one of the solutions for a randomly generated instance (see Figure 3.11.

4 .4 Limitations and future research

For simplicity, no restrictions to part-part associations are not considered. Future extensions of our approach should consider part compatibility. Additionally, contingency suppliers, as studied by Tomlin [2006], can be introduced as an alternative to increasing sourcing flexibility. This type of suppliers should require lower development efforts.

Our results show that the investigated risk measures are complementary. As future research, it would be interesting to combine them in an integrated approach. The sensitive additive approach could serve as a basis augmented by the overall risk budget measure that acts as an overarching set of constraints to capture supplier development effort. The weakest link approach could be added for individual parts to capture the risk related to new materials, technologies, or inexperienced suppliers.

5 Data Availability Statement

The data that support the findings of this study are openly available in Mendeley Data at https://data.mendeley.com/datasets/m3rrb8tpfv/3. Please refer to the third version of the data set.

6 Funding

This work was supported by the FCT - Fundação para a Ciência e a Tecnologia under Grant PD/BD/114379 Ref. CRM:0026749.

Bibliography

Mehdi Amini and Haitao Li. Supply chain configuration for diffusion of new products: An integrated optimization approach. *Omega*, 39(3):313–322, 2011.

Philippe Artzner, Freddy Delbaen, Jean-Marc Eber, and David Heath. Coherent measures of risk. *Mathematical finance*, 9(3):203–228, 1999.

Aharon Ben-Tal and Arkadi Nemirovski. Robust solutions of linear programming problems contaminated with uncertain data. *Mathematical programming*, 88(3):411–424, 2000.

Dimitris Bertsimas and Melvyn Sim. The price of robustness. *Operations Research*, 52(1): 35–53, 2004.

Gema Calleja, Albert Corominas, Carme Martínez-Costa, and Rocío de la Torre. Methodological approaches to supply chain design. *International Journal of Production Research*, 56(13):4467–4489, 2018.

Chun-Hung Chiu, Tsan-Ming Choi, and Xun Li. Supply chain coordination with risk sensitive retailer under target sales rebate. *Automatica*, 47(8):1617–1625, 2011.

Jiarui Fang, Lei Zhao, Jan C Fransoo, and Tom Van Woensel. Sourcing strategies in supply risk management: An approximate dynamic programming approach. *Computers & Operations Research*, 40(5):1371–1382, 2013.

Thiam-Soon Gan and Martin Grunow. Concurrent product and supply chain design: a literature review, an exploratory research framework and a process for modularity design. *International Journal of Computer Integrated Manufacturing*, 29(12):1255–1271, 2016.

Thiam-Soon Gan, Moritz Steffan, Martin Grunow, and Renzo Akkerman. Concurrent design of product and supply chain architectures for modularity and flexibility: process, methods, and application. *International Journal of Production Research*, pages 1–20, 2021.

Daniel J Garcia and Fengqi You. Supply chain design and optimization: Challenges and opportunities. *Computers & Chemical Engineering*, 81:153–170, 2015.

Dominic Gates. Will 787 program ever show an overall profit? Analysts grow more skeptical. https://www.seattletimes.com/business/boeing-aerospace/will-787-program-ever-show-an-overall-profit-analysts-grow-more-skeptical/, October 2015. URL https://www.seattletimes.com/business/boeing-aerospace/will-787-program-ever-show-an-overall-profit-analysts-grow-more-skeptical/. Last checked on Jan 24, 2019.

Stephen C Graves and Brian T Tomlin. Process flexibility in supply chains. *Management Science*, 49(7):907–919, 2003.

Stephen C Graves and Sean P Willems. Optimizing the supply chain configuration for new products. *Management science*, 51(8):1165–1180, 2005.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: I. unknown probability distributions. *Computers & Chemical Engineering*, 84:568–598, 2016.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Ii. a priori bounds for known symmetric and asymmetric probability distributions. *Computers & Chemical Engineering*, 101:279–311, 2017a.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Iii. exact and near-exact a posteriori expressions for known probability distributions. *Computers & Chemical Engineering*, 103:116–143, 2017b.

Gerd J Hahn and Heinrich Kuhn. Value-based performance and risk management in supply chains: A robust optimization approach. *International Journal of Production Economics*, 139(1):135–144, 2012.

Faiza Hamdi, Ahmed Ghorbel, Faouzi Masmoudi, and Lionel Dupont. Optimization of a supply portfolio in the context of supply chain risk management: literature review. *Journal of Intelligent Manufacturing*, 29(4):763–788, 2018.

Rick Hesse. Triangle distribution: Mathematica link for excel. *Decision Sciences Journal*, 31(3):12–14, 2000.

William Ho, Tian Zheng, Hakan Yildiz, and Srinivas Talluri. Supply chain risk management: a literature review. *International Journal of Production Research*, 53(16):5031–5069, 2015.

Zhen Hong, CKM Lee, and Linda Zhang. Procurement risk management under uncertainty: a review. *Industrial Management & Data Systems*, 118(7):1547–1574, 2018.

Dana Hull. Musk still in production hell as gigafactory delays model 3. https://www.bloomberg.com/news/articles/2017-11-01/tesla-delays-model-3-goals-as-early-bottlenecks-worsen-cash-burn, November 2017. URL https://www.bloomberg.com/news/articles/2017-11-01/tesla-delays-model-3-goals-as-early-bottlenecks-worsen-cash-burn. Last checked on Jan 24, 2019.

Armin Jabbarzadeh, Behnam Fahimnia, and Fatemeh Sabouhi. Resilient and sustainable supply chain design: sustainability analysis under disruption risks. *International Journal of Production Research*, 56(17):5945–5968, 2018.

Walid Klibi, Alain Martel, and Adel Guitouni. The design of robust value-creating supply chain networks: a critical review. *European Journal of Operational Research*, 203(2): 283–293, 2010.

Haitao Li and Mehdi Amini. A hybrid optimisation approach to configure a supply chain for new product diffusion: a case study of multiple-sourcing strategy. *International Journal of Production Research*, 50(11):3152–3171, 2012.

Jian Li, Shouyang Wang, and TC Edwin Cheng. Competition and cooperation in a single-retailer two-supplier supply chain with supply disruption. *International Journal of Production Economics*, 124(1):137–150, 2010.

Sebastian Pashaei and Jan Olhager. Product architecture and supply chain design: a systematic review and research agenda. *Supply Chain Management: An International Journal*, 20(1):98–112, 2015.

R Tyrrell Rockafellar. Coherent approaches to risk in optimization under uncertainty. In *OR Tools and Applications: Glimpses of Future Technologies*, pages 38–61. Informs, 2007.

Fatemeh Sabouhi, Mir Saman Pishvaee, and Mohammad Saeed Jabalameli. Resilient supply chain design under operational and disruption risks considering quantity discount: A case study of pharmaceutical supply chain. *Computers & Industrial Engineering*, 126:657–672, 2018.

R Sreedevi and Haritha Saranga. Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. *International Journal of Production Economics*, 193:332–342, 2017.

Srinivas Talluri, Thomas J Kull, Hakan Yildiz, and Jiho Yoon. Assessing the efficiency of risk mitigation strategies in supply chains. *Journal of Business Logistics*, 34(4):253–269, 2013.

Christopher Tang and Brian Tomlin. The power of flexibility for mitigating supply chain risks. *International journal of production economics*, 116(1):12–27, 2008.

Christopher S Tang, Joshua D Zimmerman, and James I Nelson. Managing new product development and supply chain risks: The boeing 787 case. In *Supply Chain Forum: An International Journal*, volume 10, pages 74–86. Taylor & Francis, 2009.

Brian Tomlin. On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management science*, 52(5):639–657, 2006.

Debby Wu, Emi Okada, and Kotaro Hosokawa. Apple, Foxconn executives to meet amid iPhone X production strain. https://asia.nikkei.com/Business/Apple-Foxconn-executives-to-meet-amid-iPhone-X-production-strain, October 2017. URL https://asia.nikkei.com/Business/Apple-Foxconn-executives-to-meet-amid-iPhone-X-production-strain. Last checked on Jan 24, 2019.

Anastasios Xanthopoulos, Dimitrios Vlachos, and Eleftherios Iakovou. Optimal newsvendor policies for dual-sourcing supply chains: A disruption risk management framework. *Computers & Operations Research*, 39(2):350–357, 2012.

Biao Yang and Ying Yang. Postponement in supply chain risk management: a complexity perspective. *International Journal of Production Research*, 48(7):1901–1912, 2010.

Haisheng Yu, Amy Z Zeng, and Lindu Zhao. Single or dual sourcing: decision-making in the presence of supply chain disruption risks. *Omega*, 37(4):788–800, 2009.

A Appendices

A .1 Notation

Indices and Sets	
$s, i, j \in S$	Supplier candidates
$p \in P$	Parts sourced
$(i, j), i < j \in S' \subset S \times S$	Pairs of supplier with overlapping part portfolios
$(p, s) \in PS' \subset P \times S$	Suppliers s capable of producing parts p
$(p, i, j) \in APSS' \subset P \times S \times S$	Parts that can be jointly integrated by both supplier i and j
$(p, i, j) \in NPSS' \subset P \times S \times S$	Parts that cannot be jointly integrated by both supplier i and j
Decision Variables	
$x_{i,j}$	1, if supplier i and j are in the same module ($= 0$ otherwise)
$y_{p,s}$	1, if part p is sourced from supplier s ($= 0$ otherwise)
Parameters	
$h_{i,j}$	0, if module is single sourced 1, if module is double sourced

Input Parameters	
Γ	Uncertainty budget for the overall risk budget approach
$\Gamma_{p,s}$	Uncertainty budget for each part-supplier pair in the weakest link approach
Γ_s	Uncertainty budget for each supplier in the additive approach
$\bar{r}_{(p,s)}$	Maximum deviation of integration risk for pair (p,s)
Uncertain Variables	
$\tilde{r}_{(p,s)}$	Integration risk considering uncertainty
$\xi_{(p,s)}$	Normalised deviation of the integration risk for (p,s)
Decision Variables	
λ	Auxiliary dual variable for the overall risk budget approach
λ_s	Auxiliary dual variable for all suppliers s for the additive approach
$\mu_{(p,s)}$	Auxiliary dual variable for all pairs (p,s)

A .2 Transformation of Robust Optimisation Constraints Into Dual Version

In order to use RO on the overall risk budget and additive approaches, the constraints dealing with risk need to be transformed into tractable problems. The robust counterpart for the constraints dealing with risk for the additive approach were shown to be given by Constraints (3.33), re-stated below. They take into account the uncertain parameter $\tilde{r}_{(p,s)}$ and hold feasibility over an uncertainty set U_s^a.

$$\begin{aligned} \sum_{(p,s)\in PS'} \left[\tilde{r}_{(p,s)}\right] \cdot y_{(p,s)} \leq RHS, \forall s \in S \\ \sum_{(p,s)\in PS'} \left[r_{(p,s)} + \bar{r}_{(p,s)} \cdot \xi^a_{(p,s)}\right] \cdot y_{(p,s)} \leq RHS, \forall s \in S \\ RHS_i := R_a \cdot \left[\sum_{(i,j)\in S'} [x_{(i,j)} \cdot (1 + h_{(i,j)})] + \sum_{(j,i)\in S'} [x_{(j,i)} \cdot (1 + h_{(j,i)})]\right], \forall i \in S \end{aligned} \tag{3.33}$$

$\bar{r}_{(p,s)}$ represents the maximum variation for each risk estimate $r_{p,s}$ from the IRM. The above semi-infinity constraints can then be re-written as follows:

$$\sum_{(p,s)\in PS'} (r_{(p,s)} \cdot y_{(p,s)}) + \max_{\xi^a \in U_s^a} \sum_{(p,s)\in PS'} (\bar{r}_{(p,s)} \cdot \xi^a_{(p,s)} \cdot y_{(p,s)}) \leq RHS,\ \forall s \in S \tag{3.34}$$

It should be noted that a quadratic optimisation problem has to be solved in (3.34). To produce a tractable robust counterpart we first formulate the primal sub-problem (3.35) for every supplier ($\forall s \in S$) and transform it into its dual version (3.36):

$$\begin{aligned} \max \quad & \sum_{(p,s)\in PS'} \bar{r}_{(p,s)} \cdot \xi^a_{(p,s)} \cdot y_{(p,s)} \\ \text{s.t.:} \quad & \sum_{(p,s)\in PS'} \xi^a_{(p,s)} \leq \Gamma_s, \forall s \in S \\ & 0 \leq \xi^a_{(p,s)} \leq 1,\ \forall (p,s) \end{aligned} \tag{3.35}$$

$$\begin{aligned} \min \quad & \Gamma_s \cdot \lambda_s + \sum_{(p,s)\in PS'} \mu_{(p,s)} \\ \text{s.t.:} \quad & \lambda_s + \mu_{(p,s)} \geq \bar{r}_{(p,s)} \cdot y_{(p,s)}, \forall (p,s) \\ & \lambda_s,\ \mu_{(p,s)} \geq 0,\ \forall (p,s) \end{aligned} \tag{3.36}$$

Finally, as show in in Bertsimas and Sim [2004], the tractable robust counterpart is obtained in constraints (3.37) by incorporating the dual auxiliary problems (3.36) into constraints (3.33).

$$\text{s.t.:} \quad \sum_{(p,s)\in PS'} [r_{(p,s)} \cdot y_{(p,s)}] + \left[\Gamma_s \cdot \lambda_s + \sum_{(p,s)\in PS'} \mu_{(p,s)}\right] \leq RHS, \forall s \in S \tag{3.37}$$

$$\lambda_s + \mu_{(p,s)} \geq \bar{r}_{(p,s)} \cdot y_{(p,s)},\ \forall (p,s) \in PS' \tag{3.38}$$

$$\lambda_s,\ \mu_{(p,s)} \geq 0,\ \forall (p,s) \in PS' \tag{3.39}$$

This transformation produces a tractable set of constraints so RO can be applied on the additive approach to risk. A similar transformation can be obtained for the overall risk budget approach by using general parameters for Γ and λ that are not indexed by supplier.

A .3 Algorithm 1 From Guzman et al. [2017]

Algorithm 1 Search algorithm to find Γ_i which satisfies ε_i^{prio}.

function MATCHPROBTHETABISECTION($\varepsilon_i^{prio}, B(\theta, \Gamma_i), \Gamma_i(\theta), tol$)
    input:
        desired probability of constraint violation ε_i^{prio} for constraint i
        probability bound $B(\theta, \Gamma_i)$ ▷ Equation (3 .4)
        function Γ_i (see Equation 3.51)
        convergence tolerance tol
    output:
        uncertain set parameter Γ_i which guarantees ε_i^{prio}
    ► Initialisation
    Set θ^U such that $B(\theta^U, \Gamma_i(\theta^U)) > \varepsilon_i^{prio}$
    $\theta^L \leftarrow 0, \theta \leftarrow (\theta^L + \theta^U)/2, \Gamma_i \leftarrow \Gamma_i(\theta), p_i \leftarrow B(\theta, \Gamma_i)$
    ► Iterate until convergence
    while $|\varepsilon_i^{prio} - p_i| > tol$ **do**
        if $p_i < \varepsilon_i^{prio}$ **then**
            $\theta^U \leftarrow 0$
        else
            $\theta^L \leftarrow \theta$
        end if
        $\theta \leftarrow (\theta^L + \theta^U)/2, \Gamma_i \leftarrow \Gamma_i(\theta), p_i \leftarrow B(\theta, \Gamma_i)$
    end while
    return Γ_i
end function

A .4 Implementing Right Triangular Distributions in Robust Optimisation

Guzman et al. [2017a] use equation (3.40) as the MGF associated with the PDF for an asymmetric triangular distribution with $a+b+c=0$. There are two issues with fitting the proposed distributions for $\tilde{r}_{(p,s)}$ to this formulation. First, with $a=c$, the denominator in the MGF is equal to zero, so the MGF must be rewritten for a right triangular distribution. Furthermore, the parameters require an offset of $-1/3$ to satisfy the condition $a+b+c=0$. For this purpose, each distribution has been initially defined with $a=c=-1/3$ and $b=2/3$, and then corrected back to the original range, which will also produce an effect on the MGF.

$$M_{\xi}(\theta) = \frac{2T(\theta)}{(b-a)(b-c)(c-a)} \tag{3.40}$$

Therefore, consider a triangular distribution with lower bound $a=0$, upper bound $b=1$ and mode $c=0$. For any given distribution, the MGF is determined using equation (3.41).

$$M_X(\theta) = E[e^{\theta X}] = \int_{-\infty}^{+\infty} e^{\theta x} f_X(x)dx \tag{3.41}$$

$$f_X(x) = \begin{cases} 0 & x < a \\ \frac{2(x-a)}{(b-a)(b-c)} & a \leq x < c \\ \frac{2}{(b-a)} & x = c \\ \frac{2(b-x)}{(b-a)(b-c)} & c < x \leq b \\ 0 & x = b \end{cases} \tag{3.42}$$

Using the PDF for a triangular distribution found in equation (3.42), the integral for the MGF can be written for the range between a and b. Note that for a right triangular distribution with $a=c$, only the range $c<x\leq b$ yields a non-zero integral. As such, equations (3.43) - (3.45) show the steps necessary to achieve the MGF shown in equation (3.46).

$$M_X(\theta) = \int_c^b e^{\theta x} \frac{2(b-x)}{(b-a)(b-c)} dx \tag{3.43}$$

$$M_X(\theta) = 2\int_c^b \frac{be^{\theta x}}{(b-a)(b-c)} dx - 2\int_c^b \frac{xe^{\theta x}}{(b-a)(b-c)} dx \tag{3.44}$$

$$M_X(\theta) = \left[\frac{2be^{\theta x}}{\theta(b-a)(b-c)}\right]_c^b - \left[\frac{2e^{\theta x}(\theta x - 1)}{\theta^2(b-a)(b-c)}\right]_c^b \tag{3.45}$$

$$M_X(\theta) = 2\frac{e^{b\theta} - e^{ct}(b\theta - c\theta + 1)}{\theta^2(b-a)(b-c)} \tag{3.46}$$

From this expression, the CGF, which is given by the natural logarithm of the MGF becomes:

$$\Lambda_X(\theta) = ln\left(2\frac{e^{b\theta} - e^{ct}(b\theta - c\theta + 1)}{\theta^2(b-a)(b-c)}\right) \tag{3.47}$$

The necessary correction to the MGF is given by equation (3.48), where d is the offset between the two distributions. To estimate the probability of violation in the constraints dealing with uncertainty, the CGF is defined as the natural logarithm of the MGF. Since the logarithm of a product is the sum of the logarithms of the factors, CGF is defined by equation 3.49.

$$M_{X+d}(\theta) = exp(b\theta)M_X(\theta) \tag{3.48}$$

$$\Lambda_{X+d}(\theta) = ln[exp(d\theta)M_X(\theta)] = d\theta + ln\left(2\frac{e^{b\theta} - e^{ct}(b\theta - c\theta + 1)}{\theta^2(b-a)(b-c)}\right) \tag{3.49}$$

The algorithm developed by Guzman et al. [2017a] solves the optimisation problem found on the right-hand side of equation (3.50) and requires four inputs: the desired probability of constraint violation, the probability bound (equation (3.50)), the function for $\Gamma_s(\theta)$ given by equation (3.51), and the convergence tolerance. A bisection algorithm is employed using values of θ, finding at each point the corresponding value of Γ_s and then calculating the probability of constraint violation. This probability is then compared with the desired probabilistic bound. The algorithm runs while the difference between the probability found and the one desired exceeds the chosen tolerance.

$$Pr\left\{\sum_j r_{ij}y_j + \sum_{j\in J_i} \xi_{ij}\bar{r}_{ij}y_j > R_i\right\} \leq exp\left(\min_{\theta>0}\left\{-\theta\Gamma_i + \sum_{k\in K_i}(d\theta + \Lambda_{ij}(g_{ij}\theta))\right\}\right) \tag{3.50}$$

$$\Gamma_s(\theta^\star) = \sum_{p\in P}\left(\left.\frac{d\Lambda_{ps}(\theta)}{d\theta}\right|_{\theta^\star} + d\right) \tag{3.51}$$

Chapter 4

Discrete Choice Model for Understanding the Role of Sustainability on Market Demand

The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning

Nuno Falcão e Cunha[*†] · **Pedro Amorim**[*†] · **Bernardo Almada-Lobo**[*†]

Working Paper

Companies and organisations from the aviation sector have made a commitment since 2005 to halve CO_2 emissions by 2050. This paper proposes an analysis on the aircraft specifications that have impacted demand from commercial airlines over the years, and whether these are in line with environmental and social sustainability policies. A conditional discrete-choice model is implemented to estimate the impact on demand from nine distinct aircraft specifications: fuel consumption, winglet adaptation, approach and take-off noise levels, maximum and cruise operating speeds, maximum and minimum seating capacities, and maximum take-off weight. The demand model estimates the impact on demand in three settings: coefficients for acquisitions between 2016 and 2020; evolution of the coefficients between 1981 and 2020, in 5-year horizons; difference in coefficients between traditional and low-cost commercial airlines. Airlines in general, and low-cost carriers to a greater extent, are found to prioritise aircraft with low fuel consumption and improved winglets. Furthermore, companies favour aircraft with lower approach noise levels. However, the corollary associated with the pursuit of more powerful engines is an accentuated demand for aircraft associated with high take-off noise levels.

Keywords: Aviation Industry · Discrete Choice Model · Sustainability · Fleet Management

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal

1 Introduction

In 2005, faced with worrying CO_2 numbers, through the ATAG, the aviation industry announced a commitment to halve CO_2 emissions by 2050, compared to the values measured that year. In 2019, the worldwide sector was responsible for 12% of CO_2 transportation related emissions. For comparison, road transport accounted for 74%. However, due to the difference in business volume, air transport averages nearly seven times the emissions in grams of CO_2 per passenger per kilometre, with respect to road transport. Globally, this sector contributes for 2% of human-induced emissions. A further commitment made by the ATAG was to halt the rise of net emissions by 2020 [ATAG, 2020]. Even though the COVID-19 pandemic inadvertently contributed to this outcome, this effect is temporary and current reports suggest a return to the 2019 air traffic by 2023. As more aircraft take off to the skies, the challenge remains of optimising individual aircraft efficiency [Bouwer et al., 2021].

The sector's pursuit for environmental, but also economic sustainability has had three major axes: innovation in aircraft and engine design, investment in alternative fuels, and the pursuit for the next generation of propulsion technology [INEA, 2020]. Thus, OEMs invested on technological innovations such as advanced aerodynamics, sophisticated avionics, composite materials and winglets [Mattos et al., 2003]. Notwithstanding the commitment made by agents across the entire industrial sector, airlines are faced with a difficult trade-off between sustainability practices and their passengers' interests. While there is extensive research on how companies may best leverage these innovations, it is unclear whether environmental sustainability is at the forefront of the airlines' fleet composition requirements.

This work is centred around three core objectives. First, to assemble a unified database of aircraft acquisitions from the last six decades, along with each aircraft's specifications. Second, using this data, to measure how aircraft specifications correlate to their demand, and assess how the perception of their utility has evolved over time. Finally, this survey will provide insight on whether airlines prioritise sustainable attributes, or if financial and route-specific considerations are more influential tie-breakers.

Building on the work of Irwin and Pavcnik [2004], a conditional discrete choice demand model is developed to estimate the weight from aircraft attributes in fleet acquisition decisions. The airline's goal is to maximise utility. In this setting, utility is defined as a linear function of the aircraft's complete set of specifications, along with non-tangible airline-specific preferences. The model estimates the perceived utility of each aircraft for each airline. Thus, it is possible to derive relative utilities for the aforementioned range of attributes (e.g., fuel consumption, noise levels, cruise speed, etc.). Furthermore, by solving the model for acquisitions made in different decades, trends regarding the evolution of these priorities over time can be mapped. A by-product of this analysis is a market share predictor for future aircraft models, based on their predicted specifications.

Overall, the present work studies the impact of aircraft specifications on demand in three settings. First, which attributes contributed positively and negatively to boost each model's acquisitions from 2016 to 2020. Here, lower fuel consumption, improved winglets, low approach noise and maximum operating speed were found to improve an aircraft's market share. Second, the evolution of impact coefficients between 1981 and 2020, within 5-year intervals. Generally speaking, commercial airlines have always prioritised fuel efficiency, but while they have been concerned with approach noise, their pursuit of more powerful engine is compromising the reduction of take-off noise levels. Finally, an analysis on the difference in priorities between traditional and low-cost commercial airlines is carried out. Low-cost carriers are found to be more influenced by low fuel consumption and improved winglets.

The discrete choice model may also allow OEMs to forecast demand, decide on necessary production capacity, and predict how they will compete with existent models. This is especially valuable in this industry due to the high non-recurring costs (e.g., development and certifications) and long product life cycles. Furthermore, this analysis looks to understand the airlines' interest in pursuing the environmental sustainability target. It will weigh whether attributes directly linked to sustainability or route-specific considerations are more important in fleet management practices. This does not mean that companies disregard their sustainability goals, but they may be forced to choose faster or larger planes to fulfil customer demand. Especially in the wake of disruptive events that put pressure across all the nodes within the industrial sector, priorities must be clearly outlined. This is the only way suppliers, OEMs, airlines, and airports can come together to ensure the recovery of the sector.

The remainder of this paper is structured as follows. Section 2 provides a review of the research on sustainability analysis for the commercial aviation sector, multi-objective fleet management models, along with methods to test the extent to which these are implemented by the industry. Section 3 outlines the data gathering processes for this work, including aircraft acquisitions since 1959 and detailed specifications of all aircraft models. Section 4 describes the discrete choice demand model developed to test the contributions from aircraft specifications to market demand. Section 5 details the outputs from the different settings used as input for the demand model and provides insight on airline sustainability priorities. Section 6 concludes the paper.

2 Literature Review

In the outset of this paper, it is important to map the main aircraft attributes that are generally considered as influential to the sustainability of airlines' operations. A relevant concurrent review is made on the state of the art of multi-objective models that consider the objectives of fleet planning and will provide insight on other valuable aircraft specifications. In line with the present work's main goal, a further assessment of demand impact methods was carried out, along with how insight from such methods has been used to influence market behaviour.

Current literature on environmental sustainability for the aviation industry looks at three major axes. Firstly, there are reports assessing fuel performance, noise and other sustainability metrics of current and past commercial aircraft (e.g., Aygun and Turan [2021], Antoine and Kroo [2005] and Givoni [2007]). Furthermore, research has been done on the optimisation of aircraft operations. An emergent example is the work done on improving trajectories to enhance aircraft sustainability. Hammad et al. [2020] review 543 papers and highlight the social and environmental benefits that can be achieved through more sophisticated aircraft trajectory optimisation. Finally, there are studies on the introduction of disruptive materials (e.g., composite materials) to reduce aircraft weight, thus improving fuel efficiency, such as Calado et al. [2018]. Along the same line of research, there are also studies on alternative fuel sources (e.g., fuel cell technology) [Renouard-Vallet et al., 2010].

While environmental sustainability has been a major concern for commercial airlines, as per the ATAG commitment [ATAG, 2021], companies must also ensure their own economic sustainability. Khoo and Teoh [2014] propose a bi-objective dynamic model that aims to maximise profit and minimise environmental impact. For the latter point, they introduce the Green Fleet Index to measure conformity with environmental requirements, which combines multiple Green Indices weighted using an AHP approach. Baykasoğlu et al. [2019] go on to propose a decision support system using fuzzy-stochastic mathematical programming for tactical sustainable fleet management. The authors analyse the case-study of a Turkish airline carrier and develop the model to make fleet size and composition decisions taking into consideration economic, time and environmental oriented objectives.

In general, there is extensive literature on both qualitative and quantitative recommendations to enhance the sustainability of air transportation. However, more insight is needed on how commercial airlines prioritise these goals versus their business interests. Irwin and Pavcnik [2004] developed a discrete choice demand model that established how governmental subsidies impact aircraft OEMs and the introduction of new products into the market. This is an extension to Berry [1994] which introduced supply-and-demand analysis for oligopoly markets, as is the case of the aviation sector.

Thus, understanding the extent to which environmental aspects penetrate the decision process for commercial airlines is not trivial. Niewiadomski [2017] assess how the agents along the air transport production network interact and how these models can influence the market outlook. Klein and Genßler [2010] suggest that customisation may be the main driver for demand as the number of different aircraft models is constantly increasing to fit the airlines' business requests. Pustelnik [2016] further classify the aviation industry as environmentally recalcitrant by highlighting the lack of action from ICAO in establishing specific policy binding aircraft operators towards environmental action. The authors suggest that global governmental action is needed to ensure progress towards the 2050 commitment to decrease CO_2 emissions.

This paper aims to extend the literature on discrete choice models for the aviation sector by including acquisition data between 1981 and 2020 (previous work used data from 1975 to 1998). Furthermore, the range of specifications is expanded to nine total attributes. The choice of the attributes introduces an additional contribution from this paper by comparing the prioritisation of aircraft characteristics with direct impact on environmental and social sustainability against a parallel array which is more oriented to the airlines' specific operations.

3 Data Gathering

Currently, there are over three thousand airlines operating around the world. Due to the necessity to restrict the analysis, the top one hundred ranked airlines in the world were chosen, according to Skytrax [Skytrax, 2019]. As an indicator to the relevance of this sample, the twenty largest airlines own a third of all aircraft in the world, all of which are part of this list [SAirportcodes, 2019]. This data was extended to include the top twenty low cost carriers. Skytrax conducts surveys to identify the best airlines both in terms of the maintenance levels of their aircraft, and quality of their services. The decision to select this range was based on the likely correlation with careful fleet management practices.

The initial data collected included over thirty thousand aircraft deliveries of new and used aircraft. These encompass one-hundred and seventy nine unique aircraft models, from twenty-three OEMs. This information was gathered from open source repositories such the Planespotters platform [Planespotters, 2021].

For each aircraft model, the information compiled includes the corresponding OEM, model designation, and date of delivery. Furthermore, the specifications required to assemble the discrete choice demand model were put together, including fuel capacity, winglet configuration, sideline, take-off and approach noise levels, cruise and maximum speeds, range, minimum and maximum seat capacity, and maximum take-off weight. This data was used to establish, for each aircraft, an array with nine key specifications. First, fuel consumption in litres per kilometre, which is estimated by finding the ratio between fuel capacity and maximum range, at maximum take-off weight. The winglet configuration results in a binary attribute indicating whether or not the aircraft was installed with improved wingtips to further improve fuel efficiency. Both of these are considered as hybrid financial and environmentally sustainable attributes. Franssen et al. [2004] report considerate impact on the life quality of the communities around Schipol airport in Amsterdam, hence approach and take-off noise levels, in decibels, were used as both environmental and social sustainability metrics. MMO, or maximum operating speed, cruise speed, minimum and maximum seating capacity, and maximum take-off weight were established as operations related attributes. The latter set of specifications is thus associated with the downstream demand from the public. Most of the information was available directly from the OEMs own websites and technical reports. Furthermore, certification reports from EASA, along with some of the online repositories listed above were used to complete the necessary information. This information is outlined in Table 4.1. The mean values are calculated across the unique aircraft models, without weighing the relative number of acquisitions.

Determining aircraft prices is the most complex step in this process. In the past, the only publicly available data were list prices, but OEMs no longer reveal them [Burbaite, 2019]. Thus, list prices were gathered directly when available, or extrapolated from group order values. It should however be noted that these prices are unlikely to be applicable to real acquisitions since they usually result from bundled orders, which should have a quantity based discount, or more complex funding/leasing operations. The resources used for this compilation included The Journal of Commerce, Flight Global, Aero Affaires, Aerocorner and Modern Airliners databases, the Airliners.net forums for pilots, along with the publicly available information from Airbus, Boeing and Embraer. Prices were corrected for inflation up to the year 2019 [1].

4 Methodology

4 .1 Overview

Discrete choice models are a widely used, tractable and efficient method for estimating the structure that drives demand. These models in particular are used for markets where the utility of consumers is driven by product differentiation and the customers' individual taste parameters. Berry [1994] was one of the first to propose its application to an oligopoly market, followed by Irwin and Pavcnik [2004]. In this context, the OEMs are set as price-setting oligopolists, and the airlines make decisions of which aircraft to acquire. While the proposed framework does not consider purchases made by individual customers, it will derive product-level market shares through the consolidation of customer decisions.

One of the main drawbacks of these models has to do with its ambition to estimate the correlation between demand and a predetermined set of differentiating characteristics. Since these models behave poorly if this array has too many variables, selecting them implies simultaneous insight into the problem and the incurring selection bias. This dimension

[1] Calculation based on the inflation calculator available at smartasset.com

Description of Data Gathered		
Number of Acquisitions	28,931	
Number of Airlines (Customers)	121	
Number of Aircraft Models	179	
Years	1959 - 2021	
Aircraft Specification	*Mean*	*Std. Dev.*
FUEL CONSUMPTION (L/KM)	58350	65500
TAKE-OFF NOISE (DB)	87.9	8.2
APPROACH NOISE(DB)	97.4	5.1
MMO (MACH)	0.81	0.14
CRUISE SPEED (KPH)	837	148
MTOW (KG)	6379	4040
SEAT MIN	166	105
SEAT CAP	215	153

Table 4.1: Descriptive statistics of data collected on aircraft deliveries between 1959 and 2021 [Planespotters, 2021].

is included in the sampling error. A further issue comes from the endogeneity of certain attributes, such as price. Indeed, it is likely that OEMs set list prices for aircraft based on their demand forecast, which in the case of the aviation sector would translate into longer backlogs. This would mean that the most sought after products command a disproportional price if the comparison were to be centred exclusively around objective specifications. Petrin and Train [2010] suggest a method to handle endogeneity in these situations. However, due to the difficulty in determining the prices associated with both new and used aircraft, since these depend on bundling decisions and ad-hoc negotiations, the present work will not include price in its analysis.

According to Dahlberg and Eklöf [2003], the conditional logit, multinomial logit, and probit logit models generally lead to similar conclusions, except for too parsimonious models. In this research, a conditional logit model will be implemented that considers a wide range of aircraft alternatives, and the incurring specifications. In this section, we present the general econometric discrete choice model and the theory behind it. In Section 5 , the variations of the model will be outlined in greater detail, along with the results. These variations will look at the following settings: aircraft purchasing priorities over the last five years (2016-2020); evolution of specifications ranking over the last four decades (1981-2020); difference in criteria between low cost carriers traditional operators; influence of customer's (airline's) geographic location.

4 .2 Conditional Discrete Choice Model

Building on the work of Benkard [2004] and Irwin and Pavcnik [2004], which looked at segments of aircraft acquisitions between 1975 and 1998, we develop a discrete choice model with the intent of understanding how an aircraft's specifications impact the probability of an airline adding it to their fleet. Additionally, we expose how some of the customer's own attributes influence that decision, such as their business model or presence around the globe. This customer choice-centric, alternative-specific is often referred to as McFadden's choice model [McFadden et al., 1973].

Each aircraft is modelled as an array of characteristics including fuel capacity, winglet adaptation, take-off and approach noise levels, cruise and maximum operating speeds, range, minimum and maximum seat capacities, and maximum take-off weight. These characteristics were chosen to represent a mixture of sustainability-oriented and route-specific attributes. This approach also considers non-tangible variables, e.g. airline preference for certain OEMs or models. For simplicity, aircraft acquisitions are considered as individual transactions. While it is common practice for airlines to bundle their orders, this would required knowledge of individual deals instead of list prices for aircraft. Additionally, this introduces random taste factors associated with ad-hoc negotiations which cannot be represented by discrete choice models.

Moreover, in our model, airlines are utility-maximising. Let subscript i denote an airline looking to acquire an aircraft, and let subscript j denote an aircraft. Depending on the year, the airline selects one of the aircraft available from all available OEMs. For the purpose of this paper, due to data availability restrictions, the year the aircraft is delivered is considered as the purchase instance. In reality, for new aircraft, airlines must finalise the purchasing agreement years in advance, depending on the OEM's backlog. As such, the utility of aircraft j for airline i is described in Equation 4.1.

$$u_{ij} = x_j \cdot \beta + \zeta_j + \tau_{ij} \tag{4.1}$$

The utility is thus a linear function of the aircraft's specifications, x_j. It further depends on ζ_j and τ_{ij} which are unobservable by the researcher. ζ_j aggregates j's specifications valued by the airlines. It should be noted that, according to Irwin and Pavcnik [2004], it's likely that OEMs set prices according to the product's quality and their knowledge of the market. Thus, there is a predictable correlation between price and and the unobserved quality ζ_j. Subsequently, τ_{ij} translates airline i's specific taste for aircraft j. According to the aforementioned literature, τ_{ij} translates consumer tastes which are identically and independently distributed for both aircraft and airlines, and assume an extreme value distribution. The utility is a construct of this model and is therefore a latent variable.

To build a conditional logit model, the observations in our data are taken as binary indicators, representing which aircraft the airline decided to have delivered at each instance. The available aircraft for each year is denoted as set A_t, and contains a sub-set of the one-hundred and seventy nine unique aircraft models, from twenty-three OEMs. Building on previous models, we consider deliveries between 1981 and 2020. Let $y_{ij} = \{0,1\}$, where $y_{ij} = 1$ in case airline i chooses to acquire aircraft j, with $j \in A_t$. Let $\theta_j = (x_j, \zeta_j)$ be an array of the aircraft's listed attributes, along with the ones valued by the customers. Irwin and Pavcnik [2004] includes detailed derivations of the resulting mean utility level, δ_j, which can be written as shown in Equation 4.2. The predicted aggregate market share of aircraft j, here interpreted as the probability of airline i choosing to acquire j, i.e., $P(y_{ij} = 1|\theta_j)$, is showing in Equation 4.3.

$$\delta_j \equiv x_j \cdot \beta + \zeta_j \tag{4.2}$$

$$P(y_{ij} = 1|\theta_j) = \frac{exp(\delta_j)}{\sum_{A_t} p(\delta_j)} \tag{4.3}$$

5 Results and Discussion

As mentioned in Section 4 .1, three distinct computational experiments are carried out. The first will analyse how airlines prioritised each of the chosen aircraft specifications based on acquisitions made between the years 2016 and 2020. The second set of regressions aims to study how these priorities have evolved since 1981, by estimating the relative priorities in five year slots. Finally, the main differences between low cost and traditional commercial airlines will be gauged in terms of how different business models rank the listed specifications.

All computational experiments followed scripts implemented using STATA/MP 15.1 for Windows (64-bit x86.64) on an Intel(R) Core(TM) i7-4790 CPU @3.60GHz with 16.0Gb of RAM, under a Windows 8.1 Pro Operating System.

5 .1 Recent Priorities Concerning Aircraft Specifications

The first discrete choice regression is aimed at the estimation of the effects of both sustainability and operations-oriented aircraft attributes on the demand from commercial airlines. Table 4.2 displays the coefficients associated with each of the attributes outlined previously, along with the associated standard error. Before interpreting the model's output, it should be noted that for the time period 2016 to 2020, all the estimations are significant, as all p-values were below 0.01.

Specification	Coefficient	Std. Err.
FUEL CONSUMPTION (L/KM)	-0.5428868***	0.0136472
WINGLET	0.3962387***	0.3962387
TAKE-OFF NOISE	0.1241448***	0.0058371
APPROACH NOISE	-0.1480856***	0.0107653
MMO (MACH)	7.658572***	0.6208932
CRUISE SPEED	-0.0085521***	0.0005882
MTOW	-4.89E-06***	6.45E-07
SEAT MIN	0.0041711***	0.0007251
SEAT CAP	0.0140067***	0.0007014
Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$		

Table 4.2: Estimating the effects of sustainability and operating specifications on airline purchases between 2016 and 2020.

The first two aircraft specifications cannot be said to be exclusively related to sustainability. Firstly, in this context, fuel consumption is estimated as the ratio between fuel capacity and maximum range, which translates to the OEM's announced fuel expenditure per kilometre, at maximum take-off weight. The winglet attribute refers to improved modifications on the aircraft's wingtips from the base model which would result in additional fuel savings. Even though these attributes result in reduced CO_2 emissions from burning less fuel, this also reduces the resources used by the airlines and optimises their operation and financial aspects. Even so, a higher fuel consumption is estimated to result in less demand for the aircraft, while the improved winglet adaptations are estimated to have increased the aircraft's market share, within the last five years. These are a good example of combining environmental sustainability with the company's own economic sustainability and are in line with the commitment to reduce environmental impact.

The following pair of attributes, however, are more tightly linked with environmental, and even social sustainability. Therefore, our analysis reveals a negative contribution from approach noise. It should be noted that, since the units for each attribute are very distinct, the relative nominal values of the coefficient do not represent in a trivial way their relative impact. Despite this, aircraft which produce more noise during take-off seem to be procured at higher rates. This is surprising, especially since a correlation between these two values could be anticipated, for the same aircraft. As outlined in Table 4.1, the take-off noise level tends to be lower than the approach noise levels, with the mean values being 87.9 dB and 97.4 dB, respectively, which means a difference of 9.5 dB. However, nearly half of the sales within this time period came from the most popular six aircraft, all of them producing approach noise levels below that threshold, while presenting above average take-off noise values, which results in this positive correlation with demand. These six models include Boeing's 787-9 Dreamliner and Airbus's A350-900, two of the most advanced aircraft in the market. A much more considerable improvement can be seen in approach noise levels, which can likely be attributed to the increased room for improvement on the approach, as outlined by NASA [Lockard and Lilley, 2004]. Whereas the engine must develop maximum power during take-off, on approach noise improvements have been made for landing, airframe and engine noise.

Another interesting result comes from the ensuing pair of attributes, both related to speed. On one hand, the MMO which is the maximum operating speed represented in Mach number (i.e., ratio to the speed of sound) has a high coefficient for impact on demand. On the other, the aircraft's cruise speed is estimated to have a negative, albeit nearly negligible effect. In fact, due to the use of light composite materials, the aforementioned aircraft are among the fastest aircraft in the market with MMO values above 0.9 Mach, but announce a cruise speed around 900kph, for fuel economy reasons. Furthermore, the MMO values for the most popular aircraft do not diverge greatly from these values, but prefer even lower cruise speeds to limit fuel consumption. Finally, the aircraft that advertise higher cruise speeds are the long-range wide-body aircraft such as Boeing's 747, which represent a very small number of sales volume.

The final pair of attributes concerns seating availability within aircraft. The minimum seating is associated with the configuration with the highest number of different classes, whereas the maximum seating capacity is, according to Skybrary [2020], the number of people that can be safely evacuated in under ninety seconds. The apparent low impact of these specifications is likely related to the customisation described by Klein and Genßler [2010], as this is the most diverse characteristic among aircraft models, as shown by the standard deviations in Table 4.1.

Overall, the hybrid sustainability and operations attributes related to fuel consumption seem to be the most sought after attributes. Even if MMO is by far the best predictor for demand, the distribution among the most popular aircraft is very flat and a by-product of the technological evolution in terms of materials and engines, but has no practical influence since aircraft operate at lower, more fuel efficient speeds.

5 .2 Evolution of Specification Priorities Over Time

Figures 4.1 and 4.2 show the estimates for the effects of the nine specifications described previously between 1981 and 2020. For these estimates, separate conditional logit regressions were made for each group of five years. For each of these time periods, the assumption that airlines could acquire the same aircraft in each of those five years was made, for simplicity. The list of aircraft purchased in each time period, however, is not the same. Since this analysis required eight different regressions, a further caveat should be noted that it is not trivial to compare the coefficients estimated across time periods. This results from the interdependence within each 5-year period of the impact coefficients since, as the impact factor for one attribute increases, the others are likely to decrease. Still, trends regarding constant positive, or negative, influence on the aircraft's market share will produce useful insight.

As before, the coefficients estimated by the logit discrete choice model were labelled according to their p-value, which is related to their significance. Coefficients which were omitted or yielded p-values above 0.1 were excluded from the analysis.

Unsurprisingly, in Figure 4.1, fuel consumption is consistently demonstrated to produce a negative impact on demand. Even if in the past fuel was cheaper and there were no environmental studies, the airline always stood to profit from expending less resources. Nevertheless, it is likely that the increased pressure from the ATAG commitment and from the price of fossil fuels led airlines to increase their preference on this axis.

The inconsistency with the evolution of the winglet adaptation attribute can be attributed to three distinct factors. First, as mentioned above, the variability of other coefficients.

Furthermore, this metric is defined as an add-on to the standard model, which was very rare in first years of this analysis, thus being present in very small numbers among those fleets. Over the years, even if they gained popularity, it should be expected for them to be less prevalent since more recent models already have optimised wingtips incorporated in base models. A final point should be made regarding only five of the seven regressions where this attribute can be used showing this as a significant attribute (this adaptation was not available prior to 1986).

The difference between the relative weights of the noise attributes is the same as the one outlined in Section 5 .1. Further supporting the improvements made in reducing approach noise levels over the years, the negative impact it has on demand has become more prevalent in recent decades. Subsequently, the increase in engine power further exacerbates the takeoff noise issue, whose weight has followed the inverse trend.

Regarding the speed-related attributes in Figure 4.2, their impact appears to have been negligible for most time periods, with airlines giving mode importance to fuel consumption, maximum take-off weight and minimum seating capacity in the intermediate five-year slots. The importance of the MMO attribute in the earliest time slot results from a combination of consistently high values announced across all planes at the time, along with low impact from most other attributes, between 1981 and 1985. Conversely, the cruise speed had a very negative impact on demand as it was during these years that the Boeing 747 entered the market.

Even though seat cap and cruise speed do not yield much impact on demand between 1986 and 2015, the minimum seating and maximum take-off weight had a considerable impact during those periods. This is undoubtedly correlated to the general increase in aircraft size over the years, with one-class configuration flights being a relatively recent concept, hence the low influence of the maximum seating capacity predictor.

Following this analysis, not only were the fuel consumption related attributes the most meaningful priorities for commercial airlines in recent years, they also appear as the most consistently impactful over the years. While there does seem to be a growing attention to approach noise level reduction, the same cannot be said for take-off noise so it is unclear whether this is a conscious choice, or if it is a result of natural upstream technological evolution. Consequently, for most years, business oriented aircraft attributes were found to have positive impact on demand, as airlines sought customised models to better suit passenger demand.

5 .3 Influence of Business Model on Specification Priorities

The final analysis obtained with the discrete choice demand model is a comparison between the priorities for the top twenty low cost-commercial airlines and the remaining companies.

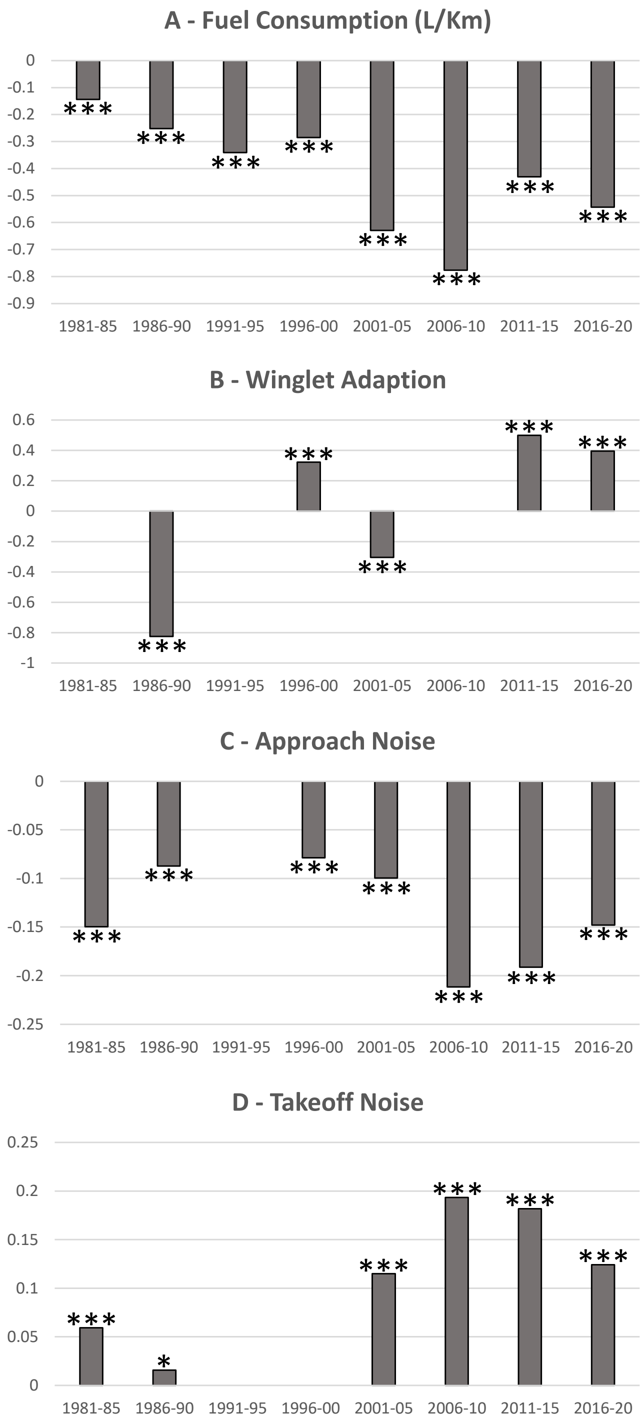


Figure 4.1: Evolution of estimates for the effects of fuel consumption (A), winglet adaptation (B), approach (C) and take-off (D) noises on airline purchases between 1981 and 2020. Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

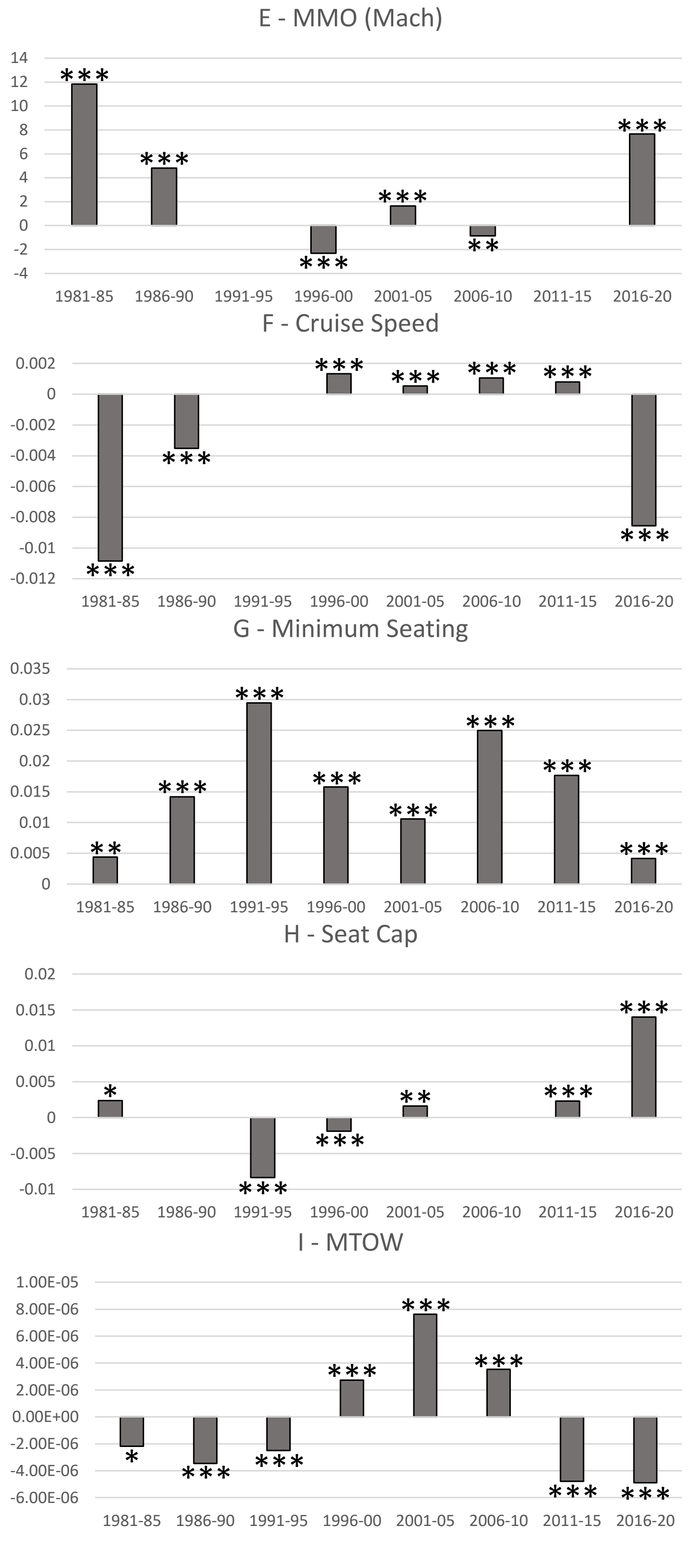


Figure 4.2: Evolution of estimates for the effects of fuel consumption (A), winglet adaptation (B), approach (C) and take-off (D) noises on airline purchases between 1981 and 2020. Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4.3 displays the estimated coefficients for the nine aforementioned aircraft specifications, for the time periods 2011 to 2015 and 2016 to 2020, for these two business models: traditional and low-cost. It is worth mentioning again that since these results come from four independent regressions, it is not trivial to compare the nominal values of the coefficients. Furthermore, the *p*-values must be taken into account, as they disqualify certain coefficients due to insufficient significance (e.g., approach noise level for low cost companies from 2011 to 2015, and the MMO value for traditional airlines from 2011 to 2015).

Even if these results are analysed in relative terms, it is clear that low cost carriers are much more concerned with selecting a fleet with low fuel consumption, and more optimised winglet adaptations. As mentioned in the previous Section, newer aircraft models will already have these built-in. However, since low cost airlines have a high incentive towards fleet commonality, i.e., adopting a single model, they are more likely to seek these adaptations [Brüggen and Klose, 2010]. Both of these observations are in line with a business model which operates with lower profit margins and must optimise every aspect of its operations.

A surprising observation is the lower coefficient for low cost operators in terms of approach noise levels, when compared with their counterparts. However, this is likely a byproduct of the heterogeneity of traditional fleets. A less surprising finding is the lack of concern regarding take-off noise as they are unlikely to invest on specifications that buffer or compromise their engines' performance during take-off, or otherwise.

The lower MMO coefficient estimated for the 2016 to 2020 window has to do, once again, with the homogeneity of the fleets associated with low cost airlines, which, for the most part, have not adopted the new and more expensive aircraft such as Boeing's 787 and Airbus's A350. Concurrently, low cost companies are likely to prioritise aircraft with slightly lower cruise speeds among an aircraft's sub-models to save on fuel consumption.

Finally, as low cost carriers operate exclusively with single-class configurations, it is surprising that they do not attribute a higher priority to the maximum seating capacity. However, this is likely the result of limitations in the data used for these regressions. Since each aircraft's standard specifications were sourced from the OEM, they do not include customised versions. Since low cost airlines often request modifications to increase seating size, it is likely that the impact factor for this attribute is underestimated in this analysis.

6 Conclusion

Following the commitment made by the ATAG, a coalition of companies and organisations in the aviation sector, to halve CO_2 emissions by 2050, compared to the values measured in 2005, the present work aims to test the commercial airlines' pursuit of sustainability metrics. More specifically, the analysis within this paper looks to establish whether companies prefer

	Low Cost		Traditional	
Specification	2011-15	2016-20	2011-15	2016-20
FUEL CONSUMPTION	-1.1098***	-1.1397	-0.3480***	-0.4501***
WINGLET	0.7069***	0.4538***	0.3766***	0.3469***
APPROACH NOISE	0.0590#	-0.3147***	-0.1782***	-0.1318***
TAKE-OFF NOISE	0.3860***	0.2730***	0.1387***	0.096991***
MMO (MACH)	8.8896***	4.1621***	-0.1811#	8.8530***
CRUISE SPEED	0.0007***	-0.0114***	0.0007***	-0.0079***
MTOW	6.50E-06***	-4.35E-06**	-5.94E-06***	-5.30E-06***
SEAT MIN	0.0313***	0.0236***	0.0145***	0.0006#
SEAT CAP	-0.0126***	0.0100***	0.0039***	0.0149***

Note: # $p > 0.1$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4.3: Estimating the effects of sustainability and operating specifications on airline purchases between 2016 and 2020.

environmentally and socially sustainable aircraft when making fleet management decisions. Alternatively, airlines may prioritise aircraft more suited to the public's demand for shorter travel time or increased seating capacity.

For this purpose, a database comprising nearly thirty thousand aircraft deliveries between 1959 and 2021, with one-hundred and seventy-nine unique aircraft models is compiled. For each aircraft, an array of nine specifications geared towards sustainability and operations defined. On the sustainability front, this includes fuel consumption, winglet adaptation, along with approach and take-off noise levels. The maximum and cruise operating speeds, the maximum and minimum seating capacities, and the maximum take-off weight are included as route-specific or market-oriented attributes.

A conditional discrete-choice demand model is implemented to estimate the impact of each of these characteristics on airline demand. This analysis is performed in three different settings: relevance of each attribute on market demand between 2016 and 2020; evolution of impact coefficients between 1981 and 2020, evaluated in 5-year horizons; comparison of specification priorities between traditional and low-cost commercial operators.

The insight derived from this analysis can support decisions for multiple stakeholders across the aviation market structure. First, it can be used by commercial airlines to assess if their current fleet management policies are in line with their medium to long-term goals and influence future acquisitions. On the OEM side, it can be used in tandem with demand forecast tools and simultaneously predict market adoption for products under development, as well as steer future product design strategies to better suit the market's needs.

6 .1 Discussion

Based on the coefficients estimated for the impact of the nine aforementioned specifications, fuel consumption, approach noise and cruise speed appear to have a negative influence on demand. Reduced fuel consumption simultaneously contributes to a positive environmental outcome and to the companies' profits. Reduced approach noise results in improved quality of life for populations around airports and limits the effects on the surrounding ecosystems. Possible explanation for the negative impact from high cruise speeds may be that the long-range wide-body aircraft present the highest values for this attribute, and command relatively low sales volume. Additionally, increased cruise speed negatively impacts fuel efficiency. On the other hand, winglet adaptation, take-off noise, maximum operating speed and seating capacities have a positive impact on demand. As for winglet adaptation, since it is associated with optimised fuel efficiency, it results in the same hybrid contribution as reduced fuel consumption. Having both maximum operating speed and take-off noise with positive coefficients likely means that airlines have a strong preference for potent engines, which must be used at maximum power during take-off. Finally, the increase in air traffic up to the start of the COVID-19 pandemic probably led airlines to look to increase seating capacity, both in multi-class and single-class configurations.

The first finding from the evolution of the estimated coefficients between 1981 and 2020 was the consistent preference for aircraft with reduced fuel consumption. The same could not be established for winglet adaptations. In the first 5-year periods, this techonology was either non-existent or in its earlier stages. Later on, there does seem to be a preference for this characteristic, except between 2001-05. This variation can be linked to most OEMs now including the optimised winglets in base models. Approach and take-off noises consistently display the same behaviour observed between 2016 and 2020. Both maximum and cruise operating speeds had inconsistent impact on demand, with the effects outlined above being a recent trend. The minimum seating has consistently had a positive impact on demand, whereas the maximum seating capacity has only demonstrated the same effect since 2001. Compared to its scale, maximum take-off weight appears to always have had a relatively low influence on fleet management decisions.

The final analysis which compared traditional and low-cost commercial airlines highlighted the latter's concern with improved aircraft operating efficiency, with noticeably lower coefficients for fuel consumption, along with higher coefficients for winglet adaptations. Since low-cost airlines actively pursue fleet commonality, they are more likely to seek winglet adaptations than new aircraft with this technology already incorporated. Unsurprisingly, low-cost airlines also select aircraft with higher take-off noise levels at a much higher rate. While there is not much divergence regarding the coefficients for seating capacity, this can be caused by the lack of information of customised seating arrangements that low-cost airlines request, since our database only considers the base version of each aircraft.

6 .2 Limitations and Future Research

The main limitation associated with this research is the accessibility to data on aircraft customisation and acquisition details. While the negotiation regarding unique alterations to aircraft base models is exclusive to the acquisition of new aircraft, these negotiations are likely to represent the airline's explicit priorities in aircraft selection. Furthermore, the greatest distinction between the decision to buy a new or used aircraft is most likely linked to the price. This is undoubtedly the most complex attribute to estimate since it is nearly unique for individual aircraft due to bundled purchases, ad-hoc negotiations and may even depend on how far in advance the airline commits to purchasing the aircraft. The most likely route to solving this limitation would be a collaboration with the OEMs' sales departments.

The introduction of price brings another degree of complexity to the discrete-choice model since it will introduce endogeneity into the problem. Since companies often attribute higher prices to products in higher demand, simply introducing price as an independent variable would incorrectly estimate that airlines look to pay as much as possible when acquiring an aircraft. Thus a preliminary regression is required to produce an appropriate estimation of the price's impact on demand.

Bibliography

Nicolas E Antoine and Ilan M Kroo. Framework for aircraft conceptual design and environmental performance studies. *AIAA journal*, 43(10):2100–2109, 2005.

ATAG. Facts and figures, 2020. URL https://www.atag.org/facts-figures.html(3/7/2021). [Online; accessed 6/5/2021].

ATAG, 2021. URL https://www.atag.org/component/news/?view=pressrelease&id=120. [Online; accessed 6/5/2021].

Hakan Aygun and Onder Turan. Environmental impact of an aircraft engine with exergo-life cycle assessment on dynamic flight. *Journal of Cleaner Production*, 279:123729, 2021.

Adil Baykasoğlu, Kemal Subulan, A Serdar Taşan, Nurhan Dudaklı, Murat Turan, Erdin Çelik, and Özgür Ülker. Development of a web-based decision support system for strategic and tactical sustainable fleet management problems in intermodal transportation networks. In *Lean and Green Supply Chain Management*, pages 189–230. Springer, 2019.

C Lanier Benkard. A dynamic analysis of the market for wide-bodied commercial aircraft. *The Review of Economic Studies*, 71(3):581–611, 2004.

Steven T Berry. Estimating discrete-choice models of product differentiation. *The RAND Journal of Economics*, pages 242–262, 1994.

Jaap Bouwer, Steve Saxon, and Nina Wittkamp. Mckinsey & company. back to the future? airline sector poised for change post-covid-19, Jun 2021. URL https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-covid-19. [Online; accessed 2/7/2021].

Alexander Brüggen and Levin Klose. How fleet commonality influences low-cost airline operating performance: Empirical evidence. *Journal of Air Transport Management*, 16 (6):299–303, 2010.

Ruta Burbaite. Why did airbus stop publishing aircraft list prices?, 7 2019. URL https://www.aerotime.aero/22798-why-did-airbus-stop-publishing-aircraft-list-prices#:~:text=According%20to%20recent%20media%20reports,not%20released%20its%202019%20data. [Online; accessed 13/7/2021].

Elcin Aleixo Calado, Marco Leite, and Arlindo Silva. Selecting composite materials considering cost and environmental impact in the early phases of aircraft structure design. *Journal of Cleaner Production*, 186:113–122, 2018.

Matz Dahlberg and Matias Eklöf. *Relaxing the IIA assumption in locational choice models: A comparison between conditional logit, mixed logit, and multinomial probit models*. Nationalekonomiska institutionen, 2003.

EAM Franssen, CMAG Van Wiechen, NJD Nagelkerke, and E Lebret. Aircraft noise around a large international airport and its impact on general health and medication use. *Occupational and environmental medicine*, 61(5):405–413, 2004.

Moshe Givoni. Environmental benefits from mode substitution: comparison of the environmental impact from aircraft and high-speed train operations. *International Journal of Sustainable Transportation*, 1(4):209–230, 2007.

Ahmed WA Hammad, David Rey, Amani Bu-Qammaz, Hanna Grzybowska, and Ali Akbarnezhad. Mathematical optimization in enhancing the sustainability of aircraft trajectory: A review. *International Journal of Sustainable Transportation*, 14(6):413–436, 2020.

INEA. Towards climate-neutral aviation: Contributions from horizon 2020 projects implemented by the innovation and networks executive agency. 2020.

Douglas A Irwin and Nina Pavcnik. Airbus versus boeing revisited: international competition in the aircraft market. *Journal of international economics*, 64(2):223–245, 2004.

Hooi Ling Khoo and Lay Eng Teoh. A bi-objective dynamic programming approach for airline green fleet planning. *Transportation Research Part D: Transport and Environment*, 33:166–185, 2014.

Michael Klein and Thomas Genßler. Model-driven data maintenance for configuration systems to tackle the challenges of mass customisation and organisational forgetting with focus on the aviation industry. *INFORMATIK 2010. Service Science–Neue Perspektiven für die Informatik. Band 1*, 2010.

David P Lockard and Geoffrey M Lilley. The airframe noise reduction challenge. 2004.

Bento Mattos, Antonini Macedo, and Durval Silva Filho. Considerations about winglet design. In *21st AIAA Applied Aerodynamics Conference*, page 3502, 2003.

Daniel McFadden et al. Conditional logit analysis of qualitative choice behavior. 1973.

Piotr Niewiadomski. Global production networks in the passenger aviation industry. *Geoforum*, 87:1–14, 2017.

Amil Petrin and Kenneth Train. A control function approach to endogeneity in consumer choice models. *Journal of marketing research*, 47(1):3–13, 2010.

Planespotters. Deliveries, 2021. URL https://www.planespotters.net/deliveries. [Online; accessed 16/1/2021 through 27/5/2021].

Pawel Pustelnik. *European struggles and American resistance: inclusion of aviation into the EU ETS*. PhD thesis, Cardiff University, 2016.

Gwénaëlle Renouard-Vallet, Martin Saballus, Gerrit Schmithals, Johannes Schirmer, Josef Kallo, and K Andreas Friedrich. Improving the environmental impact of civil aircraft by fuel cell technology: concepts and technological progress. *Energy & Environmental Science*, 3(10):1458–1468, 2010.

SAirportcodes. Emergendy evacuation on land, 2019. URL https://airportcodes.io/en/blog/top-20-biggest-airlines-by-fleet-size/. [Online; accessed 13/7/2021].

Skybrary. Emergendy evacuation on land, Dec 2020. URL https://www.skybrary.aero/index.php/Emergency_Evacuation_on_Land. [Online; accessed 13/7/2021].

Skytrax. World's top 100 airlines 2019, 2019. URL https://www.worldairlineawards.com/worlds-top-100-airlines-2019/. [Online; accessed 2/5/2021].

Chapter 5

Conclusions and Future Work

This thesis studies the main sustainability challenges faced by the aerospace sector in recent decades by looking at how the industry's products, supply chains and market structures have evolved. Throughout this thesis, mathematical and empirical models were introduced to support important commitments and disruptive restructuring decisions of the industry's echelons. The first challenge concerns the process of scouting, testing and introducing new materials and technologies into aircraft production. The long planning horizons, high non-recurring costs associated with development and certification, along with low production volumes and long product life cycles make this a particularly complex challenge for the sector. Additionally, following the trend towards more modular product and supply chain designs and the incurring integration, the transition to system integrators was explored. Considering the issues reported with this shift in supply chain structure, the problem of concurrent product and supply chain design was extended through the inclusion of a collaborative proactive supply chain risk management mechanism. Furthermore, the impact of environmental commitments and CO_2 emission targets on aircraft specifications and fleet management decisions was analysed. This way, the thesis achieves a global overview of how sustainability can be pursued by all stakeholders across the aerospace sector's value chain.

1 Contributions

Broadly speaking, this thesis contributes to the literature on sustainable product and supply chain innovation for the aerospace industry. The thesis provides companies in different echelons of the aerospace sector with quantitative tools that support decisions related with the introduction of new materials and technologies, the incurring necessary supply structure, while account for changes in the supply chain structure. It is important to note that some of the contributions listed in this Section can also be applied to other high-tech industries with similar production volumes and/or similar supply chain structures, e.g. the shipping industry.

The first contribution of this thesis is present both in Chapters 2 and 3 and has to do with the collaboration with OEMs from the aerospace sector. Due to the market structures' current resemblance to a duopoly, the literature involving real case studies is very diminished, despite being fundamental towards improving both academic research and corporate decisions. Gaining access to real data, and exchanging insight with practitioners is the only way to validate models and ensure their applicability.

This way, the second contribution was a decision support tool designed to map the evolution and new trends of aerospace supply chains, combining several methodologies that identify and characterise stakeholders. The network connecting these agents, along wtih their engagement and priorities towards sustainability was also defined. The second layer of the framework includes a CP-SCD model that provides policies for robust supply chain design. To improve the OEM's resilience, the model combines efficient allocation of resources with concurrent supply chain risk management mechanisms and makes decisions on the modularity level of aircraft components. This way, suppliers and parts are assembled in modules with the goal of reducing the workload at the final assembly site. The tool is further complemented by a hybrid simulation performance assessment tool that analyses the selection of new materials and manufacturing processes through a trade-off analysis between different sustainability metrics. A subsequent mixed integer programming model was applied to optimise those metrics. Some reformulations and high efficiency methods were also included in this study to improve the quality of solutions achieved in reasonable computational time. The proposed framework can assist both suppliers and OEMs at different junctions of product and supply chain design, as well as during the planning stages for new aircraft programs.

This research was part of the IAMAT collaboration, and one of its main outputs was the following research paper:

- **Publication A**: Cátia Barbosa, **Nuno Falcão e Cunha**, Carlos Malarranha, Telmo Pinto, Ana Carvalho, Pedro Amorim, M. Sameiro Carvalho, Américo Azevedo, Susana Relvas, Tânia Pinto-Varela, Ana Cristina Barros, Filipe Alvelos, Cláudio Alves, Jorge Pinho de Sousa, Bernardo Almada-Lobo, José Valério de Carvalho and Ana Barbosa-Póvoa. Towards an integrated framework for aerospace supply chain sustainability. In *Congress of APDIO, the Portuguese Operational Research Society*, pages 1-13. Springer, Cham, 2018.

Chapter 3 included three important contributions. First, it contributed to the literature on supply chain risk management by identifying and defining a new supply chain risk type. Termed the integration risk, it is associated with the disruptions associated with the redefinition of the role of tier-1 suppliers as system integrators. Thus, it represents a qualitative assessment gauging risk exposure related to the supplier's technical and managerial capabilities in producing integrated components. Three unique approaches were introduced to account for integration risk. These impose risk thresholds on the supply chain design process, at each supply node, or for individual part-supplier associations.

Second, a novel mathematical programming model was developed and implemented for concurrent product and supply chain design, with proactive supply chain risk management mechanisms. To improve the tool's applicability to current industry procurement procedures, the inputs required for the model mirror current risk assessment practices, and combine insight from these reports to estimate integration risk. The model is an extension to the deterministic work from Gan and Grunow [2016] and Gan et al. [2021], which enforce a fixed number of suppliers for each module. The approach introduced in this thesis was optimised in terms of computational time, and introduced sourcing flexibility as a decision variable in the context of integration risk mitigation.

The third contribution draws back to the aforementioned value of collaborating with an industrial partner and, going beyond traditional validation using theoretically generated instances, the model wa validated using a real case study from a large European OEM in the aerospace industry. This collaboration with the Technical University of Munich yielded the following research paper:

- **Publication B**: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. Robust Supply Chain Design with Suppliers as System Integrators: and Aerospace Case Study. *Submitted to IJPR*, 2021

Finally, this thesis contributed to the literature on sustainability analysis on fleet management practices. First, this paper extended the work on discrete choice models for the aviation sector, which previously only analysed aircraft deliveries and acquisitions between the years of 1975 and 1998. Furthermore, these research papers are focused almost exclusively on the two largest OEMs for commercial aircraft, more specifically on the sales for wide-body models. Thus, the data collected in Section 4 refers to aircraft purchases between 1959 and 2021. Following the state of the art, the demand model implemented focused on choice decisions from 1981 to 2020.

Another contribution in this field was the expansion of the the range of specifications considered in the model to nine total attributes. Beyond the traditional array of range, passenger seating and take-off weight, the characteristics selected introduce an additional dimension to the analysis. This is achieved by comparing the prioritisation of aircraft specifications with direct impact on environmental and social sustainability against a competing set which is more oriented to the airlines' specific operations.

The results and insight from this model were presented in the research paper:

- **Publication C**: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning. *Working Paper*, 2021

2 Answers to the Research Questions

Research Question 0 *How can the development of new products and supply chains be improved in terms of sustainability, for the aerospace sector?*

The biggest challenge in improving the sustainability of the introduction of the materials and production technologies into the aerospace industry is understanding its potential to impact every echelon of the supply chain. With every innovation, it is important to identify the previous conditions, the new challenges, and also make room for subsequent improvements. This becomes more complex when stakeholders must account for the three axes of sustainability: economic, environmental and social. Thus, OEMs together with suppliers at every tier must have appropriate tools to identify incoming changes, and prepare themselves to respond to the different problem's requirements.

In this thesis, we propose an integrated framework with a triple bottom line approach to all sustainability axes, specifically geared towards NPD initiatives with the introduction of advanced materials/manufacturing processes. From the top to the bottom of the proposed framework, decision makers with a decision support tool that addresses challenges at different levels of the development process. This cross-functional system is adaptable and begins by gaining insight on industry trends and challenges, followed by quantitative models that tackle product and supply chain design, performance assessment through discrete event simulation, and optimisation of sustainability metrics.

Research Question 1 *How to model and solve concurrent Supply Chain Design and Supply Chain Risk Management decisions?*

In the past, product design was almost completely separate from the procurement process of supplier selection. More recently, these two processes have been addressed simultaneously, especially as the first tier of suppliers have been tasked with system design and supply chain management responsibilities. While models proposing collaborative product and supply chain design have already been proposed, these do not consider supply chain risk mitigation mechanisms in their solutions.

In this thesis, the first quantitative model incorporating all three dimensions is proposed and tested. For this purpose, the model's inputs are the available suppliers, which parts can be sourced from each supplier candidate and risk estimates for each part-supplier association. Instead of minimising the number of suppliers, the model's objective is to minimise the number of supplier nodes, which can be single or double sourced. This represents the OEM's strategy to integrate their supply chain into a more modular design by assigning pre-assembled modular components to suppliers. The model makes two decisions. First, which suppliers source each of the parts. Second, whether a supplier producing a part does so alone, or if there is a second supplier supplier assigned to the same module. The incurring selective sourcing flexibility, in conjunction with the possibility to vary the level of integration, depending on the risk estimations made for the parts assigned to each supplier, are the main SCRM mechanisms present in the model.

This decision support tool recognises supply chain modularity as complex decision. This way, rather than looking at the decision to integrate the supply chain as binary, the model proposes integration for some parts, while simultaneously being capable or recommending single-part supply nodes.

Research Question 2 *How to address uncertainty in the performance from suppliers acting as System Integrators using Robust Optimisation?*

The redefinition of tier-1 suppliers as system integrators was followed by disruptions associated with their inexperience with the newly acquired technical and managerial responsibilities. While there are various examples of qualitative analysis on the causes for these disruptions, a quantitative model would be of great use to support decision makers in pursuing integrated supply chains. To mitigate the effect of these issues, the newly defined integration risk was incorporated into the model described in research question 1.

To maximise the applicability of this model, the integration risk values for each supplier were estimated based on the qualitative assessment of their technical and managerial capabilities made be the OEM's procurement team. An exploratory approach was taken to consider this risk type and three distinct risk mitigation mechanisms were defined. First, the overall risk budget approach, which was found to be suitable for representing supplier management effort. Second, the weakest link approach, which is best suited for managing the introduction of a new material or technology into aircraft programmes. Finally, the additive approach takes the most advantage of module sizing possibilities and makes better adjustments to double sourcing in response to risk profiles.

The implementation of robust optimisation made it possible to consider uncertainty associated with the risk levels estimated by the OEM and test the incurring variability compared to the deterministic solutions. This made it possible to estimate the effects on supply chain associated with the incorrect assessment of suppliers, unpredictable supplier disruption, fluctuations in supplier performance over time.

Research Question 3 *How are aircraft specifications driving the demand from commercial airlines?*

To determine the impact of how the attributes associated with distinct aircraft models drives demand, a conditional discrete choice model was implemented. Three distinct experiments were made to test the effect of aircraft specifications on purchases made by commercial airlines. The analysis is centred around nine key attributes: fuel consumption, winglet adaptation, approach and take-off noise levels, MMO, cruise speed, minimum and maximum seating capacities, and maximum take-off weight.

The first regression indicated which of the aircraft models' specifications had positive and negative effect on acquisitions from 2016 to 2020. Higher fuel consumption has a negative impact on demand, but improved winglets, low approach noise and maximum operating speed were found to improve an aircraft's market share. Furthermore, a set of eight distinct regressions was carried out to establish the evolution of impact coefficients between 1981 and 2020, aggregating demand in 5-year intervals. Overall, commercial airlines have always prioritised fuel efficiency, and have preferred models with lower approach noise levels. The final set of regressions estimated the impact of the nine characteristics for traditional and low-cost commercial airlines from 2011 to 2015, and from 2016 to 2020. The most noticeable differences were found for low-cost carriers being more influenced by low fuel consumption and aircraft with optimised winglet adaptations.

Research Question 4 *What is the impact of sustainability commitments on the evolution of fleet management practices?*

Following the ATAG commitment, organisations and companies in the aviation sector have publicly announced their concern with sustainability metrics, especially in terms of CO_2 emissions. Answering research question 3 highlighted that economic and environmental sustainability can be addressed collaboratively as reducing the fuel consumption of airline fleets will both reduce operating costs and the impact on the ecosystem. Similarly, preferring aircraft which have optimised wingtips which further improve fuel efficiency in comparison to base models also achieves both of these objectives.

However, even though airlines have displayed a strong preference for aircraft with low approach noise levels, the same could not be observed for take-off noise levels. In practice, both will produce the same effect on the surrounding communities. Thus, on one hand, approach noise has been demonstrated as easier to mitigate by making adaptations to landing procedures, to the airframe itself, and improving how the engine is operated on approach. Contrarily, during take-off, the noise levels are highly associated with the engine's behaviour at maximum thrust, which is required for lift off. Thus, by observing the airlines' strong preference for aircraft with high MMO values, it can be said that airlines are not consistently concerned with the social sustainability aspects associated with noise reduction.

3 Future Work

Beyond the specific opportunities for future research outlined in each of Chapter within this thesis, the common necessity is accessibility to data and opportunities for validation. Not only is the aerospace industry associated with relatively low production volumes, the number of OEMs has shrunk from an oligopoly to a near duopoly. This leads to aircraft manufacturers withholding more information, and being more careful with protecting their intellectual property. The same is true for companies in other echelons of the aerospace supply chain, especially following the transference of engineering and management capabilities to key partners that now act as system integrators. While both Chapters 2 and 3 result from collaborations with aerospace OEMs, the accessibility to data was very limited due no the data sharing restrictions. The main path towards improving the significance and applicability of the models implemented in this thesis is through further involvement between academia and these companies.

The IAMAT collaboration proposed a cross-functional decision support system applicable to various stages of development for both product and supply chain design, associated with the planning stages for new aircraft programs. As the market structure changes, supply chain roles evolve, and with new materials and manufacturing technologies being adopted by aerospace OEMs, so too must the framework be adapted. While the first stage will remain applicable in mapping industry trends and challenges, it must feed the remaining models to consider the ensuing innovations. While this project focused on composite materials, future work must address different materials and propulsion systems, such as fully-electric aircraft.

The concurrent product and supply chain design model, with proactive supply chain risk management mechanisms is Chapter 3 can also be extended. The first improvement would be the inclusion of a Design Structure Matrix to include part-part compatibility in the model's results. The current iteration of the model includes a simplification due to its focus on part-supplier interactions, since the research focused on the integration risk which is originates from the supplier. Thus, the model allows any number of parts to be integrated into a larger module, as long as they can be sourced from the same supplier.

Moreover, the model can be adapted to include two additional supplier profiles. First, in-house facilities to support make or buy decisions. Second, while the model bases the limitation on sourcing flexibility to double sourcing on the current literature, another possible improvement is the inclusion of backup suppliers. These are companies that in the agile production of parts for urgent situations, and command a higher price for this specialised service. Both of these extensions could also lead to the inclusion of cost analysis on the collaborative product and supply chain design solutions.

The final point regarding this model would be to consider complementary application of the risk mitigation approaches. A promising prospect would be to combine the additive, weakest link and overall risk budget approaches in an integrated decision support system. The dynamic behaviour from the additive approach would be enhanced by the overall risk budget measure which could impose constraints on supplier development effort. The weakest link approach could then be defined for individual part-supplier associations to mitigate disruptions related to new materials, technologies, or inexperienced suppliers.

Finally, to improve the discrete choice demand model, much more detailed data on aircraft customisation alternatives and the incurring pricing strategies would be required. This would mean understanding the explicit priorities that airlines seek when ordering new aircraft, and how making multiple aircraft orders stands to decrease unit price. Similarly, for used aircraft, a modelling approach would be required to estimate the degradation of specifications and the incurring decrease in price. This way, a discrete choice model could be implemented to assess the decision between acquiring new and used aircraft, and what attributes influence this decision.

Increasing the number of choices and even varying the available choices for different acquisition moments could stand to increase the applicability of the model. On the other hand, using price as a variable in the model introduces endogeneity into the problem. Generally, companies associate higher prices to products in higher demand, and the same can be expected from airlines. Thus, price cannot be trivially included as an additional independent variable. Since more expensive aircraft command higher demand, this would lead the model to incorrectly estimate that higher prices have a positive effect on demand. As such, a preliminary regression is required to produce an appropriate estimation of the price's impact on demand, such as the one suggested by Petrin and Train [2010].

Complete List of References

Bibliography

Airbus. Be an airbus supplier. http://www.airbus.com/be-an-airbus-supplier.html, 2018. Accessed: 22/2/2018.

Douglas Alem, Eduardo Curcio, Pedro Amorim, and Bernardo Almada-Lobo. A computational study of the general lot-sizing and scheduling model under demand uncertainty via robust and stochastic approaches. *Computers & Operations Research*, 90:125–141, 2018.

Rafaela Alfalla-Luque, Carmen Medina-Lopez, and Heribert Schrage. A study of supply chain integration in the aeronautics sector. *Production Planning & Control*, 24(8-9): 769–784, 2013.

Nicolas E Antoine and Ilan M Kroo. Framework for aircraft conceptual design and environmental performance studies. *AIAA journal*, 43(10):2100–2109, 2005.

ATAG. Facts and figures, 2020. URL https://www.atag.org/facts-figures.html(3/7/2021). [Online; accessed 6/5/2021].

ATAG, 2021. URL https://www.atag.org/component/news/?view=pressrelease&id=120. [Online; accessed 6/5/2021].

Hakan Aygun and Onder Turan. Environmental impact of an aircraft engine with exergo-life cycle assessment on dynamic flight. *Journal of Cleaner Production*, 279:123729, 2021.

Nader Azad and Hamid Davoudpour. Designing a stochastic distribution network model under risk. *The International Journal of Advanced Manufacturing Technology*, 64(1-4): 23–40, 2013.

A Azaron, KN Brown, SA Tarim, and M Modarres. A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal of Production Economics*, 116(1):129–138, 2008.

Atefeh Baghalian, Shabnam Rezapour, and Reza Zanjirani Farahani. Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case. *European Journal of Operational Research*, 227(1):199–215, 2013.

Adil Baykasoğlu, Kemal Subulan, A Serdar Taşan, Nurhan Dudaklı, Murat Turan, Erdin Çelik, and Özgür Ülker. Development of a web-based decision support system for strategic and tactical sustainable fleet management problems in intermodal transportation networks. In *Lean and Green Supply Chain Management*, pages 189–230. Springer, 2019.

Benita M Beamon. Supply chain design and analysis: Models and methods. *International journal of production economics*, 55(3):281–294, 1998.

Wouter WA Beelaerts van Blokland, SC Santema, and Ricky Curran. Lean supply chain management in aerospace. *Encyclopedia of Aerospace Engineering*, 2010.

C Lanier Benkard. A dynamic analysis of the market for wide-bodied commercial aircraft. *The Review of Economic Studies*, 71(3):581–611, 2004.

Steven T Berry. Estimating discrete-choice models of product differentiation. *The RAND Journal of Economics*, pages 242–262, 1994.

Dimitris Bertsimas and Melvyn Sim. The price of robustness. *Operations Research*, 52(1): 35–53, 2004.

Bombardier. *Stakeholder Engagement*. Bombardier, 2018a.

Bombardier. Stakeholder engagement, 2018b.

J. Borucki and W. Pawlewski. Mixing abs and des approach to modeling of a delivery process in the automotive industry. *Communications in Computer and Information Science*, 430(ed):133–143, 2014.

Jaap Bouwer, Steve Saxon, and Nina Wittkamp. Mckinsey & company. back to the future? airline sector poised for change post-covid-19, Jun 2021. URL https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-covid-19. [Online; accessed 2/7/2021].

Alexander Brüggen and Levin Klose. How fleet commonality influences low-cost airline operating performance: Empirical evidence. *Journal of Air Transport Management*, 16 (6):299–303, 2010.

John M Bryson, Michael Quinn Patton, and Ruth A Bowman. Working with evaluation stakeholders: A rationale, step-wise approach and toolkit. *Evaluation and program planning*, 34(1):1–12, 2011.

Ruta Burbaite. Why did airbus stop publishing aircraft list prices?, 7 2019. URL https://www.aerotime.aero/22798-why-did-airbus-stop-publishing-aircraft-list-prices#:~:text=According%20to%20recent%20media%20reports,not%20released%20its%202019%20data. [Online; accessed 13/7/2021].

Elcin Aleixo Calado, Marco Leite, and Arlindo Silva. Selecting composite materials considering cost and environmental impact in the early phases of aircraft structure design. *Journal of Cleaner Production*, 186:113–122, 2018.

Felix TS Chan, Niraj Kumar, Manoj Kumar Tiwari, Henry CW Lau, and KL Choy. Global supplier selection: a fuzzy-ahp approach. *International Journal of production research*, 46(14):3825–3857, 2008.

Chun-Hung Chiu, Tsan-Ming Choi, and Xun Li. Supply chain coordination with risk sensitive retailer under target sales rebate. *Automatica*, 47(8):1617–1625, 2011.

Sunil Chopra and Manmohan Sodhi. Reducing the risk of supply chain disruptions. *MIT Sloan Management Review*, 55(3):72–80, 2014.

United Nations Global Compact and Business for Social Responsability. *Supply Chain Sustainability*. BSR, second edition, 2015.

Matz Dahlberg and Matias Eklöf. *Relaxing the IIA assumption in locational choice models: A comparison between conditional logit, mixed logit, and multinomial probit models*. Nationalekonomiska institutionen, 2003.

Deloitte. 2018 Global aerospace and defense industry outlook. On a solid profitable growth path. Technical report, 2018.

David M Dietrich and Elizabeth A Cudney. Methods and considerations for the development of emerging manufacturing technologies into a global aerospace supply chain. *International Journal of Production Research*, 49(10):2819–2831, 2011.

Jiarui Fang, Lei Zhao, Jan C Fransoo, and Tom Van Woensel. Sourcing strategies in supply risk management: An approximate dynamic programming approach. *Computers & Operations Research*, 40(5):1371–1382, 2013.

Charles Fine. Clockspeed: Winning industry control in the age of temporary advantage, 1996.

Charles H Fine and Daniel E Whitney. Is the make-buy decision process a core competence? 2002.

EAM Franssen, CMAG Van Wiechen, NJD Nagelkerke, and E Lebret. Aircraft noise around a large international airport and its impact on general health and medication use. *Occupational and environmental medicine*, 61(5):405–413, 2004.

Nickolas Freeman, John Mittenthal, Burcu Keskin, and Sharif Melouk. Sourcing strategies for a capacitated firm subject to supply and demand uncertainty. *Omega*, 77:127–142, 2018.

Thiam Gan, Moritz Steffan, Martin Grunow, and Renzo Akkerman. Concurrent design of product and supply chain architectures: Method and application for modularity and flexibility. 2017.

Thiam-Soon Gan and Martin Grunow. Concurrent product and supply chain design: a literature review, an exploratory research framework and a process for modularity design. *International Journal of Computer Integrated Manufacturing*, 29(12):1255–1271, 2016.

Thiam-Soon Gan, Moritz Steffan, Martin Grunow, and Renzo Akkerman. Concurrent design of product and supply chain architectures for modularity and flexibility: process, methods, and application. *International Journal of Production Research*, pages 1–20, 2021.

Dominic Gates. Will 787 program ever show an overall profit? Analysts grow more skeptical. https://www.seattletimes.com/business/boeing-aerospace/will-787-program-ever-show-an-overall-profit-analysts-grow-more-skeptical/, October 2015. Last checked on Jan 24, 2019.

Moshe Givoni. Environmental benefits from mode substitution: comparison of the environmental impact from aircraft and high-speed train operations. *International Journal of Sustainable Transportation*, 1(4):209–230, 2007.

Mark Goedkoop, Reinout Heijungs, Mark Huijbregts, An De Schryver, Jaap Struijs, and Rosalie Van Zelm. Recipe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*, 1, 2009.

Mark Goh, Joseph YS Lim, and Fanwen Meng. A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research*, 182(1): 164–173, 2007.

Alev Taskin Gumus, Ali Fuat Guneri, and Selcan Keles. Supply chain network design using an integrated neuro-fuzzy and milp approach: A comparative design study. *Expert Systems with Applications*, 36(10):12570–12577, 2009.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: I. unknown probability distributions. *Computers & Chemical Engineering*, 84:568–598, 2016.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Ii. a priori bounds for known symmetric and asymmetric probability distributions. *Computers & Chemical Engineering*, 101:279–311, 2017a.

Yannis A Guzman, Logan R Matthews, and Christodoulos A Floudas. New a priori and a posteriori probabilistic bounds for robust counterpart optimization: Iii. exact and near-exact a posteriori expressions for known probability distributions. *Computers & Chemical Engineering*, 103:116–143, 2017b.

Gerd J Hahn and Heinrich Kuhn. Value-based performance and risk management in supply chains: A robust optimization approach. *International Journal of Production Economics*, 139(1):135–144, 2012.

Faiza Hamdi, Ahmed Ghorbel, Faouzi Masmoudi, and Lionel Dupont. Optimization of a supply portfolio in the context of supply chain risk management: literature review. *Journal of Intelligent Manufacturing*, 29(4):763–788, 2018.

Ahmed WA Hammad, David Rey, Amani Bu-Qammaz, Hanna Grzybowska, and Ali Akbarnezhad. Mathematical optimization in enhancing the sustainability of aircraft trajectory: A review. *International Journal of Sustainable Transportation*, 14(6):413–436, 2020.

Rick Hesse. Triangle distribution: Mathematica link for excel. *Decision Sciences Journal*, 31(3):12–14, 2000.

William Ho, Tian Zheng, Hakan Yildiz, and Srinivas Talluri. Supply chain risk management: a literature review. *International Journal of Production Research*, 53(16):5031–5069, 2015.

Zhen Hong, CKM Lee, and Linda Zhang. Procurement risk management under uncertainty: a review. *Industrial Management & Data Systems*, 118(7):1547–1574, 2018.

Dana Hull. Musk still in production hell as gigafactory delays model 3. https://www.bloomberg.com/news/articles/2017-11-01/tesla-delays-model-3-goals-as-early-bottlenecks-worsen-cash-burn, November 2017. Last checked on Jan 24, 2019.

IATA. Iata technology roadmap. 2013.

IATA. Covid-19 - outlook for air transport and the airline industry. Technical report, IATA, 11 2020.

ICF. *Global Aerospace Sector M&A update*. Catalyst Corporate Finance, 2012.

INEA. Towards climate-neutral aviation: Contributions from horizon 2020 projects implemented by the innovation and networks executive agency. 2020.

Robert R Inman and Dennis E Blumenfeld. Product complexity and supply chain design. *International Journal of Production Research*, 52(7):1956–1969, 2014.

Douglas A Irwin and Nina Pavcnik. Airbus versus boeing revisited: international competition in the aircraft market. *Journal of international economics*, 64(2):223–245, 2004.

S. Jain, E. Lindskog, J. Andersson, and Johansson B. A hierarchical approach for evaluating energy trade-offs in supply chains. *International Journal of Production Economics*, 146 (2):411–422, 2013.

AK Jallow, B Majeed, K Vergidis, A Tiwari, and R Roy. Operational risk analysis in business processes. *BT Technology Journal*, 25(1):168–177, 2007.

Baruch Keren. The single-period inventory problem: Extension to random yield from the perspective of the supply chain. *Omega*, 37(4):801–810, 2009.

Omera Khan, Martin Christopher, and Bernard Burnes. The impact of product design on supply chain risk: a case study. *International Journal of Physical Distribution & Logistics Management*, 38(5):412–432, 2008.

Omera Khan, Martin Christopher, and Alessandro Creazza. Aligning product design with the supply chain: a case study. *Supply Chain Management: An International Journal*, 17 (3):323–336, 2012.

Hooi Ling Khoo and Lay Eng Teoh. A bi-objective dynamic programming approach for airline green fleet planning. *Transportation Research Part D: Transport and Environment*, 33:166–185, 2014.

Meysam Shafiei Kisomi, Maghsud Solimanpur, and Ali Doniavi. An integrated supply chain configuration model and procurement management under uncertainty: a set-based robust optimization methodology. *Applied Mathematical Modelling*, 40(17-18):7928–7947, 2016.

Michael Klein and Thomas Genßler. Model-driven data maintenance for configuration systems to tackle the challenges of mass customisation and organisational forgetting with focus on the aviation industry. *INFORMATIK 2010. Service Science–Neue Perspektiven für die Informatik. Band 1*, 2010.

Jian Li, Shouyang Wang, and TC Edwin Cheng. Competition and cooperation in a single-retailer two-supplier supply chain with supply disruption. *International Journal of Production Economics*, 124(1):137–150, 2010.

Ying Liao, Paul Hong, and S Subba Rao. Supply management, supply flexibility and performance outcomes: an empirical investigation of manufacturing firms. *Journal of Supply Chain Management*, 46(3):6–22, 2010.

David P Lockard and Geoffrey M Lilley. The airframe noise reduction challenge. 2004.

Anuja Mahashabde, Philip Wolfe, Akshay Ashok, Christopher Dorbian, Qinxian He, Alice Fan, Stephen Lukachko, Aleksandra Mozdzanowska, Christoph Wollersheim, Steven RH Barrett, et al. Assessing the environmental impacts of aircraft noise and emissions. *Progress in Aerospace Sciences*, 47(1):15–52, 2011.

Renata Mansini, Martin WP Savelsbergh, and Barbara Tocchella. The supplier selection problem with quantity discounts and truckload shipping. *Omega*, 40(4):445–455, 2012.

Bento Mattos, Antonini Macedo, and Durval Silva Filho. Considerations about winglet design. In *21st AIAA Applied Aerodynamics Conference*, page 3502, 2003.

Daniel McFadden et al. Conditional logit analysis of qualitative choice behavior. 1973.

PL Meena and SP Sarmah. Multiple sourcing under supplier failure risk and quantity discount: A genetic algorithm approach. *Transportation Research Part E: Logistics and Transportation Review*, 50:84–97, 2013.

PL Meena, SP Sarmah, and A Sarkar. Sourcing decisions under risks of catastrophic event disruptions. *Transportation research part E: logistics and transportation review*, 47(6): 1058–1074, 2011.

Frank Meisel. Multi-period supplier selection and supplier development under dynamic and uncertain demand. In *Supply Management Research*, pages 3–27. Springer, 2012.

Mary J Meixell and Vidyaranya B Gargeya. Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review*, 41 (6):531–550, 2005.

Steven A Melnyk, Ram Narasimhan, and Hugo A DeCampos. Supply chain design: issues, challenges, frameworks and solutions, 2014.

Kevin Michaels. Three predictions for the post-covid aerospace supply chain. *Aviation Week & Space Technology*, October(15-25):74, 2020.

Ronald K Mitchell, Bradley R Agle, and Donna J Wood. Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of management review*, 22(4):853–886, 1997.

Daniela Mocenco. Supply chain features of the aerospace industry particular case airbus and boeing. *Scientific Bulletin–Economic Sciences*, 14(2):17–25, 2015.

Bruna Mota, Maria Isabel Gomes, Ana Carvalho, and Ana Paula Barbosa-Póvoa. Towards supply chain sustainability: economic, environmental and social design and planning. *Journal of Cleaner Production*, 105:14 – 27, 2015. ISSN 0959-6526. doi:

https://doi.org/10.1016/j.jclepro.2014.07.052. URL http://www.sciencedirect.com/science/article/pii/S0959652614007719.

Bruna Mota, Maria Isabel Gomes, Ana Carvalho, and Ana Paula Barbosa-Póvoa. Sustainable supply chains: An integrated modeling approach under uncertainty. *Omega*, 77:32 – 57, 2018. ISSN 0305-0483. doi: https://doi.org/10.1016/j.omega.2017.05.006. URL http://www.sciencedirect.com/science/article/pii/S0305048317304401.

Maria Mrazova. Advanced composite materials of the future in aerospace industry. *Incas bulletin*, 5(3):139, 2013.

Piotr Niewiadomski. Global production networks in the passenger aviation industry. *Geoforum*, 87:1–14, 2017.

Sharon Novak and Steven D Eppinger. Sourcing by design: Product complexity and the supply chain. *Management Science*, 47(1):189–204, 2001.

Oliver Wyman. *Challenges for European aerospace suppliers*. Oliver Wyman, 2015.

Sebastian Pashaei and Jan Olhager. Product architecture and supply chain design: a systematic review and research agenda. *Supply Chain Management: An International Journal*, 20(1):98–112, 2015.

Amil Petrin and Kenneth Train. A control function approach to endogeneity in consumer choice models. *Journal of marketing research*, 47(1):3–13, 2010.

Planespotters. Deliveries, 2021. URL https://www.planespotters.net/deliveries. [Online; accessed 16/1/2021 through 27/5/2021].

Pawel Pustelnik. *European struggles and American resistance: inclusion of aviation into the EU ETS*. PhD thesis, Cardiff University, 2016.

Patrick Qiang and Anna Nagurney. A bi-criteria indicator to assess supply chain network performance for critical needs under capacity and demand disruptions. *Transportation Research Part A: Policy and Practice*, 46(5):801–812, 2012.

Masood Rabieh, Mohammad Modarres, and Adel Azar. Robust-fuzzy model for supplier selection under uncertainty: An application to the automobile industry. *Scientia Iranica*, 25(4):2297–2311, 2018.

Bill Read. Aerospace digital transformation, May 2020. URL https://www.aerosociety.com/news/aerospace-digital-transformation/. [Online; accessed 1/7/2021].

Mark S Reed, Anil Graves, Norman Dandy, Helena Posthumus, Klaus Hubacek, Joe Morris, Christina Prell, Claire H Quinn, and Lindsay C Stringer. Who's in and why? a typology of stakeholder analysis methods for natural resource management. *Journal of environmental management*, 90(5):1933–1949, 2009.

Anabela Costa Reis. *The Aerospace Industry: a Descriptive and Prospective Empirical Analysis for Portugal*. PhD thesis, Dissertação (Mestrado em Engenharia Aeroespacial). Instituto Superior ..., 2011.

Darcie Renn. Aerospace & defense. Technical report, San Francisco, CA, 2015.

Gwénaëlle Renouard-Vallet, Martin Saballus, Gerrit Schmithals, Johannes Schirmer, Josef Kallo, and K Andreas Friedrich. Improving the environmental impact of civil aircraft by fuel cell technology: concepts and technological progress. *Energy & Environmental Science*, 3(10):1458–1468, 2010.

Roland Berger. Aerostructure equipment market: Study report. Technical report, 12 2015. p.11.

Roland Berger. Aerospace industry: turning point ahead?, 2016.

Roland Berger. How the covid-19 crisis is expected to impact the aerospace industry. Technical report, 6 2020.

SAirportcodes. Emergendy evacuation on land, 2019. URL https://airportcodes.io/en/blog/top-20-biggest-airlines-by-fleet-size/. [Online; accessed 13/7/2021].

Mohsen S Sajadieh, Anders Thorstenson, and Mohammad R Akbari Jokar. Comparing sourcing strategies in two-echelon supply chains. *Computers & Operations Research*, 45:108–115, 2009.

Tadeusz Sawik. Selection of resilient supply portfolio under disruption risks. *Omega*, 41 (2):259–269, 2013.

Damien Schatteman, Willy Herroelen, Stijn Van de Vonder, and Anton Boone. Methodology for integrated risk management and proactive scheduling of construction projects. *Journal of Construction Engineering and Management*, 134(11):885–893, 2008.

N. Schieritz and A. Größler. Emergent structures in supply chains - a study integrating agent-based and system dynamics modeling. *Proceedings of the 36th Annual Hawaii International Conference on System Sciences*, 2013.

N. Schieritz and P. M. Milling. Modeling the forest or modeling the trees: a comparison of system dynamics and agent-based simulation. *Proceedings of the 21st International Conference of the System Dynamics Society*, 2003.

Ulf Schnars and Rudolf Henrich. Applications of ndt methods on composite structures in aerospace industry. In *Proceedings of the Conference on Damage in Composite Materials, Stuttgart, Germany*, pages 18–19, 2006.

Marcel Schroijen and Michel Tooren. Decision support framework for future aircraft development programs. In *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS)*, page 6930, 2009.

Hyesung Seok, Kyungdoh Kim, and Shimon Y Nof. Intelligent contingent multi-sourcing model for resilient supply networks. *Expert Systems with Applications*, 51:107–119, 2016.

Stefan Seuring. A review of modeling approaches for sustainable supply chain management. *Decision support systems*, 54(4):1513–1520, 2013.

Neranjana de Silva, Stephan Baur, Robert Thomson, Manfred Hader, Jan Gerrit Köchling, Kai Balder, Barry Neal, Oliver Hazimeh, Zhanfu Yu, Didier Bréchemier, and et al. Aerospace & defence management issues radar 2020, Dec 2020. URL https://www.rolandberger.com/en/Insights/Publications/Aerospace-Defence-Management-Issues-Radar-2020.html. [Online; accessed 6/5/2021].

Skybrary. Emergendy evacuation on land, Dec 2020. URL https://www.skybrary.aero/index.php/Emergency_Evacuation_on_Land. [Online; accessed 13/7/2021].

Skytrax. World's top 100 airlines 2019, 2019. URL https://www.worldairlineawards.com/worlds-top-100-airlines-2019/. [Online; accessed 2/5/2021].

Rebecca Slayton and Graham Spinardi. Radical innovation in scaling up: Boeing's dreamliner and the challenge of socio-technical transitions. *Technovation*, 47:47–58, 2016a.

Rebecca Slayton and Graham Spinardi. Radical innovation in scaling up: Boeing's dreamliner and the challenge of socio-technical transitions. *Technovation*, 47:47–58, 2016b.

Mahmut Sonmez. *Review and critique of supplier selection process and practices*. © Loughborough University, 2006.

R Sreedevi and Haritha Saranga. Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. *International Journal of Production Economics*, 193:332–342, 2017.

J. D. Sterman. Business dynamics: systems thinking and modeling for a complex world. 2000.

Patricia M Swafford, Soumen Ghosh, and Nagesh Murthy. The antecedents of supply chain agility of a firm: scale development and model testing. *Journal of Operations Management*, 24(2):170–188, 2006.

Babak H Tabrizi and Jafar Razmi. Introducing a mixed-integer non-linear fuzzy model for risk management in designing supply chain networks. *Journal of Manufacturing Systems*, 32(2):295–307, 2013.

Srinivas Talluri, Ram Narasimhan, and Wenming Chung. Manufacturer cooperation in supplier development under risk. *European Journal of Operational Research*, 207(1):165–173, 2010.

Srinivas Talluri, Thomas J Kull, Hakan Yildiz, and Jiho Yoon. Assessing the efficiency of risk mitigation strategies in supply chains. *Journal of Business Logistics*, 34(4):253–269, 2013.

Christopher Tang, Brian Yeh, and Joshua Zimmerman. Boeing's 787 dreamliner: A dream or a nightmare? `https://tinyurl.com/2f4fytv9`, 2013a.

Christopher Tang, Brian Yeh, and Joshua Zimmerman. Boeing's 787 dreamliner: A dream or a nightmare? UCLA Anderson Global Supply Chain Blog, 2013b.

Christopher S Tang, Joshua D Zimmerman, and James I Nelson. Managing new product development and supply chain risks: The boeing 787 case. *Supply Chain Forum: An International Journal*, 10(2):74–86, 2009.

Kenneth E Train. *Discrete choice methods with simulation*. Cambridge university press, 2009.

Karl Ulrich. The role of product architecture in the manufacturing firm. *Research policy*, 24(3):419–440, 1995.

United Nations. *Supply Chain Sustainability - A Practical Guide for Continuous Improvement - Second Edition*. United Nations, 2015.

Debby Wu, Emi Okada, and Kotaro Hosokawa. Apple, Foxconn executives to meet amid iPhone X production strain. `https://asia.nikkei.com/Business/Apple-`

Foxconn-executives-to-meet-amid-iPhone-X-production-strain, October 2017. Last checked on Jan 24, 2019.

Desheng Dash Wu, Yidong Zhang, Dexiang Wu, and David L Olson. Fuzzy multi-objective programming for supplier selection and risk modeling: A possibility approach. *European Journal of Operational Research*, 200(3):774–787, 2010.

Anastasios Xanthopoulos, Dimitrios Vlachos, and Eleftherios Iakovou. Optimal newsvendor policies for dual-sourcing supply chains: A disruption risk management framework. *Computers & Operations Research*, 39(2):350–357, 2012.

Biao Yang and Ying Yang. Postponement in supply chain risk management: a complexity perspective. *International Journal of Production Research*, 48(7):1901–1912, 2010.

Yongxiang Yang, Rob Boom, Brijan Irion, Derk-Jan van Heerden, Pieter Kuiper, and Hans de Wit. Recycling of composite materials. *Chemical Engineering and Processing: Process Intensification*, 51:53–68, 2012.

Haisheng Yu, Amy Z Zeng, and Lindu Zhao. Single or dual sourcing: decision-making in the presence of supply chain disruption risks. *Omega*, 37(4):788–800, 2009.

Min-Chun Yu, Mark Goh, and Hung-Chung Lin. Fuzzy multi-objective vendor selection under lean procurement. *European Journal of Operational Research*, 219(2):305–311, 2012.

Stuart X Zhu. Analysis of dual sourcing strategies under supply disruptions. *International Journal of Production Economics*, 170:191–203, 2015.

George A Zsidisin and Michael E Smith. Managing supply risk with early supplier involvement: a case study and research propositions. *Journal of supply chain management*, 41 (4):44–57, 2005.

Appendix A

Publications and Communications

The main outputs of the work carried out for this thesis are outlined in this chapter. Three different papers were submitted/published. Of these three papers, two resulted from international collaborations with real case-studies and have been completely finalised. The third paper is an independent venture between Nuno Falcão e Cunha, the author, and Professor Pedro Amorim, the supervisor, and Bernardo Almada-Lobo, the co-supervisor. This working paper will be submitted to an international journal. Further publications were submitted to conferences, including three extended abstracts and four abstracts.

Table A.1 outlines all relevant publications, including their type, comments on whether is was associated with a communication at a conference, the current status, along with the journal or conference to which they were submitted.

The work elaborated was presented at national conferences on seven occasions and, due to the COVID-19 pandemic, could not be communicated at the 2020 edition of the 31^{st} Annual POMMS conference, which would have taken place in Minneapolis, MN, USA.

1 Main Publications

Publication A: Cátia Barbosa, **Nuno Falcão e Cunha**, Carlos Malarranha, Telmo Pinto, Ana Carvalho, Pedro Amorim, M. Sameiro Carvalho, Américo Azevedo, Susana Relvas, Tânia Pinto-Varela, Ana Cristina Barros, Filipe Alvelos, Cláudio Alves, Jorge Pinho de Sousa, Bernardo Almada-Lobo, José Valério de Carvalho and Ana Barbosa-Póvoa. Towards an integrated framework for aerospace supply chain sustainability. In *Congress of APDIO, the Portuguese Operational Research Society*, pages 1-13. Springer, Cham, 2018.

Author Contribution to Paper A

Document	Type	Comments	Status	Journal/Conference Name
A	Journal Paper	IAMAT Collaboration	Published	IO'2018
B	Journal Paper	TUM Collaboration	Submitted	IJPR
C	Journal Paper	-	Completed	N/A
D	Extended Abstract	Presented in Porto, PT	Published	IEMS'2017
E	Extended Abstract	Presented in Porto, PT	Published	IEMS'2018
F	Extended Abstract	Presented Online	Published	IEMS'2021
G	Abstract	Presented in Valença, PT	Published	IO'2017
H	Abstract	Presented in Aveiro, PT	Published	IO'2018
I	Abstract	Presented in Tomar, PT	Published	IO'2019
J	Abstract	Cancelled due to COVID-19	Published	POMS'2020

Table A.1: Publications produced within this research.

The paper is one of the main outputs of the IAMAT project, which joined researchers from the Universidade do Minho, Universidade do Porto, Universidade Técnica de Lisboa, and MIT. Nuno Falcão e Cunha was fully responsible for section 3 .2. Nuno Falcão e Cunha was in charge of defining the overall flow of the paper, producing framework figures, and writing Sections 1 , 2 , 3 .2, and 4 . Carlos Malarranha, Cátia Barbosa and Telmo Pinto were in charge of sections 3 .1, 3 .3 and 3 .4, respectively. The remaining authors were tasked with the paper's revision.

Publication B: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. Robust Supply Chain Design with Suppliers as System Integrators: and Aerospace Case Study. *Submitted to IJPR*, 2021

Author Contribution to Paper B

The authors planed this paper to elaborate on Thiam-Soon Gan's previous supply chain design model. Nuno Falcão e Cunha defined the research questions and planed theoretical and practical experiments to answer them. Nuno Falcão e Cunha and Thiam-Soon Gan wrote the literature review and the introduction sections. Nuno and Thiam introduced the concept of integration risk for suppliers. Based on the supply chain design model from Thiam's previous paper, the model was extended to incorporate selective sourcing flexibility and integration risk. Thiam-Soon elicited and prepared all data for the real world case study (sourcing and risk data from 100 suppliers and 41 components). Nuno Falcão e Cunha structured the data so it could be used as input for the model. Nuno Falcão e Cunha contributed to the reformulation and enhancement of the efficiency of the initial supply chain design model as well as introducing the three different approaches to incorporate integration risk. Nuno Falcão e Cunha and Eduardo Curcio contributed to extending the model using the robust optimisation with integration risk uncertainty. Nuno Falcão e Cunha created the script to create randomly generated instances. Nuno conducted all experiments, analysed the results and compiled them into the figures within the paper, and derived managerial insights. One of the figures (supply chain architecture of the case study) was designed and created by Thiam-Soon Gan. The derivation of the managerial implication from the results were refined and enhanced by Professor Martin Grunow, Professor Pedro Amorim and Professor Bernardo Almada-Lobo. Nuno Falcão e Cunha contributed the most to this paper, while Thiam's industry knowledge were fundamental for the genesis and definition of this paper.

Publication C: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning. *Working Paper*, 2021

Author Contribution to Paper C

The paper is the outcome of a collaboration with both Pedro Amorim, the supervisor, and Bernardo Almada-Lobo, the co-supervisor. The topic of the paper was defined by Professor Pedro Amorim. Nuno Falcão e Cunha defined the research questions, collected the necessary data on aircraft acquisitions, aircraft specifications and nesting categories. Nuno Falcão e Cunha defined the discrete choice demand model and performed all necessary runs of the model. All sections of the paper were written by Nuno Falcão e Cunha. All the insight therein was enhanced by Professors Pedro Amorim and Bernardo Almada-Lobo, who were also in charge of the revision of the paper.

2 Additional Publications

2 .1 Extended Abstracts

- **Publication D**: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "Supply Chain Modelling and Supplier Selection in the Aerospace Industry". Porto, Portugal, 2017. Extended Abstract presented at IEMS ’17: 8th Industrial Engineering and Management Symposium, Porto, Portugal, January 2017

  Publication available at:

  https://paginas.fe.up.pt/~degi/iems17/files/bookletIEMS17.pdf

  (Included in Appendix A)

- **Publication E**: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow."Robust Supply Chain Design under Supplier Integration and Consolidation Uncertainty: an Aerospace Case-study". Porto, Portugal, 2018. Extended Abstract presented at IEMS ’18: 9th Industrial Engineering and Management Symposium, Porto, Portugal, January 2018

  Publication available at:

  https://web.fe.up.pt/~degi/iems18/files/bookletIEMS18.pdf

  (Included in Appendix B)

- **Publication F**: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning". 2021. Extended Abstract presented at IEMS ’21: 9th Industrial Engineering and Management Symposium, [Online], January 2018.

  Publication available at:

  https://paginas.fe.up.pt/~degi/iems21/files/Booklet_IMES21.pdf

(Included in Appendix C)

2 .2 Abstracts

- **Publication G**: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "Supply Chain Modelling and Supplier Selection in the Aerospace Industry". Valença, Portugal, 2017. Abstract presented at IO'17: XVIII Congresso da APDIO, Valença, Portugal, June 2017

  Publication available at:

  http://www.norg.uminho.pt/IO2017/IO2017book.pdf

- **Publication H**: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. "Robust Supply Chain Design under Supplier Integration Uncertainty". Aveiro, Portugal, 2018. Abstract presented at IO'18: XIX Congresso da APDIO, Aveiro, Portugal, September 2018

  Publication available at:

  http://apdio.pt/web/io2018/livro-de-resumos

- **Publication I**: **Nuno Falcão e Cunha**, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo. "Robust Supply Chain Design of Aerospace Supply Chains under Probabilistic Bounds for Constraint VIolation". Tomar, Portugal, 2019. Abstract presented at IO'19: XX Congresso da APDIO, Tomar, Portugal, July 2019

  Publication available at:

  http://apdio.pt/documents/241014/0/livro-resumos-apdio2019.pdf

- **Publication J**: **Nuno Falcão e Cunha**, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo. "Robust Supply Chain Design under Supplier Integration Uncertainty for the Aerospace Industry" Minneapolis, MN, USA, 2020. Presentation of abstract at POMS 31st Annual Conference Minneapolis, MN, USA, April 23-27 2020 cancelled due to COVID-19 Pandemic

3 National Conferences

- **IEMS'2017: 8th Industrial Engineering and Management Symposium**

  Presentation of project poster and elevator pitch: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "Supply Chain Modelling and Supplier Selection in the Aerospace Industry". Porto, Portugal, January 2017

  Conference Page: https://paginas.fe.up.pt/~degi/iems17/

- **IO'2017: XVIII Congresso da APDIO**

  Project presentation: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "Supply Chain Modelling and Supplier Selection in the Aerospace Industry". Valença, Portugal, June 2017

  Conference Page: `http://apdio.pt/web/io2017/home`

- **IEMS'2018: 9th Industrial Engineering and Management Symposium**

  Presentation of project poster and elevator pitch: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow."Robust Supply Chain Design under Supplier Integration and Consolidation Uncertainty: an Aerospace Case-study". Porto, Portugal, January 2018

  Conference Page: `https://web.fe.up.pt/~degi/iems18/`

- **IO'2018: XIX Congresso da APDIO**

  Project Presentation: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. "Robust Supply Chain Design under Supplier Integration Uncertainty". Aveiro, Portugal, July 2018

  Paper Presentation: Cátia Barbosa, **Nuno Falcão e Cunha**, Carlos Malarranha, Telmo Pinto, Ana Carvalho, Pedro Amorim, M. Sameiro Carvalho, Américo Azevedo, Susana Relvas, Tânia Pinto-Varela, Ana Cristina Barros, Filipe Alvelos, Cláudio Alves, Jorge Pinho de Sousa, Bernardo Almada-Lobo, José Valério de Carvalho and Ana Barbosa-Póvoa. Towards an integrated framework for aerospace supply chain sustainability. In *Congress of APDIO, the Portuguese Operational Research Society*, pages 1-13. Springer, Cham, 2018.

  Conference Page: `http://apdio.pt/web/io2018`

- **DEGI Club**

  Project Presentation: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. "Robust Supply Chain Design under Supplier Integration Uncertainty: and Aerospace Case Study". Porto, Portugal, March 2019

  Conference Page: `https://paginas.fe.up.pt/~degi/flagship-events/`

- **IO'2019: XX Congresso da APDIO**

Project Presentation: **Nuno Falcão e Cunha**, Eduardo Curcio, Pedro Amorim, Bernardo Almada-Lobo. "Robust Supply Chain Design of Aerospace Supply Chains under Probabilistic Bounds for Constraint VIolation". Tomar, Portugal, July 2019

Conference Page: http://apdio.pt/web/io2019/home

- **IEMS'2021: 12th Industrial Engineering and Management Symposium**

  Presentation of project poster and full presentation: **Nuno Falcão e Cunha**, Pedro Amorim, Bernardo Almada-Lobo. "The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning". [Online], May 2021

  Conference Page: https://paginas.fe.up.pt/~degi/iems21/

4 International Conferences

- **POMMS'2020 31st Annual Conference**

  Accepted presentation: **Nuno Falcão e Cunha**, Thiam-Soon Gan, Pedro Amorim, Bernardo Almada-Lobo, Martin Grunow. "Robust Supply Chain Design under Supplier Integration Uncertainty for the Aerospace Industry" Minneapolis, MN, USA, April 2020

  Conference Page: https://pomsmeetings.org/conf-2020/

  [Cancelled due to COVID-19 Pandemic]

Appendix A

IEMS '17 |

Extended Abstract:
8th Industrial Engineering and Management Symposium

Supply Chain Modelling and Supplier Selection in the Aerospace Industry

Nuno Falcão e Cunha[*†] · **Pedro Amorim**[*†] · **Bernardo Almada-Lobo**[*†]

1 The Challenge

The aerospace sector poses many unique challenges as companies competing in this industry become increasingly globalised. The development of a single aircraft model can take up to 15 years, including R&D, design, material selection and certification, which must all be accompanied with the assembly of a suitable supply chain capable of assembling and delivering the final product. As such, the aerospace industry has a considerable strategic component associated with it as projections must be made of market demand years in advance. The long extension of these projects brings with it a certain amount of risk that must be considered and mitigated. A sound supply chain management is fundamental to assure the venture is sustainable and that it can reach completion.

Large OEMs have recently begun to share this risk with 1st tier suppliers which help finance the development stages, and start to receive their money back after the first sale. In exchange, they have a more active role during said development and are given more

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal

autonomy in the management and selection of their own supply chain. Evaluating and comparing the supply chains behind the suppliers in each tier is a complex challenge and one that would be an important decision support system for supplier selection.

This research project is a sub-part of the IAMAT project for the introduction of advanced materials technologies into new product development for the mobility industry. Research groups from the University of Minho, FEUP, IST and MIT are working together towards a product development evaluation framework, targeted at advanced materials, manufacturing technologies and structures for the aerospace industry. The research outlined here is part of the fourth work package, supply chains towards sustainability, in charge of assessing and quantifying supply chain impacts of product design choices. Within this scope, the task at hand is to develop supply chain planning models that will serve as a decision support prototype capable of evaluating the sustainability and resilience of supply chains in the aerospace industry.

The first challenge is then to build a wide scope generalised model of the equilibrium supply chain structure for the aerospace sector. This will potentiate the study of operational trade-offs associated with decisions made during supply chain design which can be, for example, of a geographical nature or to do with means for transporting components between production and assembly sights. A global overview such as this one will analyse viable sourcing strategies, production methods, transportation, storage and other key aspects of the supply chain. The fact that this model will require a comprehensive understanding of the sector and its inner workings makes it a useful starting point that will develop awareness on the particularities of this industry.

In aerospace companies, it is usually the case that each aircraft has its own supply chain associated with it. As such, the second challenge close in on a specific focal company and will be to develop a planning model for supplier selection, which will very likely have to consider decisions made in the development for a particular aircraft. As discussed above, it is common for each supply tier to directly manage the tier below it. Therefore, selection between suppliers may consider not only technical specifications, but also supply chain decisions made downstream, which will directly influence the resilience and sustainability of the whole supply chain.

2 The Methodology

Before tackling the two challenges outlined above with modelling and optimisation algorithms, the initial approach has been to become more familiar with the aerospace sector, which involved an extensive literature review. This included papers describing the supply chain, as well as supply chain management tools and practices for the aerospace industry. Additionally, research done on supplier selection, both for the aerospace industry and for others such as the automotive sector, were investigated along with work done on developing metrics for risk-exposure assessment and management.

The characterisation of the equilibrium supply chain structure will rely on the development of a simple representation of the entire supply chain for the aerospace sector, relying on both the literature and contacts with relevant informants to make assumptions on the industry?s procedures. These assumptions will cover multiple supplier tiers, transport and storage policies, as well as interactions between stakeholders, including suppliers, OEMs and customers. This model can also provide insight on the impact that different scenarios of market demand, which must be projected years in advance, will have upstream in terms of the supply chain. These assumptions will have associated with them mathematical equations that will be used in an optimisation model capable of supporting propositions for profitable development in each section of the supply chain. These propositions will analyse trade-offs from decisions such as transporting parts by ship or by plane and will support strategic decisions by analysing the ensuing costs along the entire chain.

The second part of this project will take the form of a supplier selection decision model. The first step will be to establish critical factors that OEMs consider when choosing between suppliers for projects associated with new aircraft. These can be associated with the materials used by each supplier or lead times, but may also be metrics for reliability, sustainability or resilience. Furthermore, it may be relevant to consider what the suppliers themselves value in their own supplier selection and how that will impact the supply chain as a whole. Each of these variables will be inserted in an optimisation model that will help in objectively comparing suppliers based on the OEMs priorities. Examples of techniques to be considered with this intent are analytic hierarchy process (AHP), Fuzzy programming and data envelopment analysis (DEA).

3 The Value to Society

The aerospace industry is one in undeniable expansion, but one that with each new venture carries with it a great deal of risk. In the past, this sector has faced serious issues with delays in production and in delivering finished products to their clients. This has been due to inefficient supply chain management that was unable to keep up with the rapid globalisation of the main companies in the field. Furthermore, due to the long lead times associated with the development of the aircraft, mistakes made in supply chain design may be costly but only detected years later. As such, it is of great importance that suitable tools are developed capable of ensuring a sustainable, resilient and reliable supply chain.

The goal of the IAMAT project as a whole is to optimise innovation in the aerospace industry with an integrated framework for introducing new materials and structural solutions in mobility industries. The research outlined in this abstract will have the more specific aim of evaluating supply chain sustainability and resilience trade-offs in supply chain design related decisions. Embraer, one of the world's largest aircraft manufacturers, will serve as a test-bed for the models assembled over the course of the project and, thus, will provide most of the relevant information used within the models assembled throughout this project.

Therefore, the first contribution will be a compilation of policies and propositions on general practices for the global supply chain for the aerospace sector, with the intent of ensuring profitable development. By modelling the equilibrium supply chain structure for the aerospace sector, it will be possible to study operational trade-offs propagated throughout the supply chain for each design choice made along the way. These decisions could be, for example, the choice between different locations for production and assembly plants, choosing local or foreign suppliers, or even opting for a certain means of transportation.

Additionally, a solution methodology will be developed that will act as a supplier selection support system providing insight on metrics associated with sustainability, resilience and reliability for each decision, but also considering product design specifications such as materials, manufacturing techniques, operations costs and lead times.

Appendix B

IEMS ’18 |

Extended Abstract:
9th Industrial Engineering and Management Symposium

Robust Supply Chain Design under Supplier Integration and Consolidation Uncertainty: an Aerospace Case-study

Nuno Falcão e Cunha[*†] · **Thiam-Soon Gan**[‡] · **Pedro Amorim**[*†] · **Bernardo Almada-Lobo**[*†] · **Martin Grunow**[‡]

1 The Challenge

The aerospace sector is characterised by low production volumes with high degree of technological complexity, and long product life cycles that yield expensive aircraft development programmes. To ensure profitability, Original Equipment Manufacturers (OEMs) are forced to keep each aircraft in production for 25 to 30 years. The strategic planning of their supply chains and product portfolio plays a key role in the success of these companies.

The catastrophic events of September 11 highlighted the need for robust risk mitigation strategies as the entire industry was driven into a recession. To recover market trust, airline providers were forced lower their prices. As a result OEMs such as Airbus, Boeing and Embraer have since been pressured to reduce purchase and operating costs for their aircraft. This has motivated new, more efficient, aircraft generations using innovative technologies,

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal
‡ Technical University of Munich, Chair of Production and Supply Chain Management

such as composite materials. To support these technological advancements, aerospace supply chain management practices also had to evolve. OEMs developed more global supply chains, increasing the amount of foreign sourcing, and adopted risk-sharing partnerships with key suppliers.

With the intent of lowering costs across the entire supply chain and in order to reduce their exposure from the large investments in aircraft development programmes, certain suppliers were selected to take responsibility for part of the costs and risks. This strategy has been aggressively pursued by Airbus and Boeing, as partners have had to absorb most of the non-recurring costs involved in developing aircraft, and only begin to recuperate their investment after first sales. As a result, OEMs have since assumed the role of systems integrators and passed on considerable product design, development and manufacturing responsibilities to their suppliers. Some of these suppliers began to keep the Intellectual Property (IP) for the systems and components that they provided.

Suppliers thus had to develop their technical capabilities and OEMs began to outsource larger and more complex components of their aircraft, aiming to reduce final assembly times. The Boeing 787 Dreamliner was the biggest step in this direction, with 70% of aircraft components being outsourced and final assembly time being reduced to 3 days. Boeing hired 50 tier-1 partners that took on the role of “Integrators” and were required to deliver complete sections of the aircraft. However, the 787 programme was threatened by many problems which led to a 200% increase in development costs and schedule overrun, as some suppliers were unable to consistently fulfil their obligations. Boeing’s inclusion of some unproven technologies in the 787, such as new composite materials, meant that some suppliers did not have the technical capabilities to integrate their sections. Additionally, some partners were unable to manage their own supply chain and accurately track the performance of their own suppliers.

As more responsibility has been passed on to key partners, there has also been a consolidation wave between Tier-1 aerospace suppliers. Mergers have been one of the strategies for these companies to become resilient and to acquire certain technical capabilities. While suppliers must not be disrupted over the entire duration of the aircraft programmes, these actions may lead to the loss of planned redundancy in the OEM’s supply chain and may lead to an increase in the overall supply chain risk.

The shifts in responsibilities, and the further consolidation of Tier-1 suppliers increase their decision power within current and future aircraft programmes. As a result, the power relationship between the OEMs and the “Super Tier 1 Suppliers” is a relevant and current topic. On one hand, OEMs acknowledge the potential for new procurement synergies with greater systems integration, price bundling, and risk pooling. On the other hand, they may face the loss of negotiation power and IP.

2 The Methodology

In this research, we study the design of aerospace supply chains and supplier selection for new aerospace products. Based on the work of Gan et al. (2017), we develop a supply chain design (SCD) method that seeks an efficient and robust supply base with minimum number of supplier modules. Supplier modules contain the supplier, or group of suppliers, from which a set of parts is sourced. This model considers the risk associated with each of the suppliers selected. It will mitigate supplier modules that exceed certain risk thresholds, which are defined by decisions makers with different risk aversion. The model further allows for distinct selective sourcing flexibility for each module as a potential risk mitigation strategy.

As an input for this model, the pool of supplier candidates is represented in a Part-Supplier Matrix (PSM). The PSM contains a binary relation between parts and suppliers, and indicates whether the part can be sourced from a certain potential supplier. The corresponding integration risk for a supplier to integrate a given part is represented in the Integration Risk Matrix (IRM). The IRM evaluates this risk through 3 risk-levels: 'low', 'medium' or 'high'. Finally, the propensity for merger between each supplier pair will be represented in a Consolidation Risk Matrix (CRM). The CRM uses the same scale as the one in the IRM. Traditionally, OEMs perform their own estimations for these risks based on their knowledge of the suppliers' operations, their technical and supply chain management capabilities, and their financial condition. Portfolio similarity, or complementarity may also be taken into account when estimating the consolidation risk between two suppliers.

Robust optimisation (RO) is used to investigate how decision makers may design their supply chains to mitigate the integration and consolidation risks described in the previous section. RO is used to test the effects of uncertain integration and consolidation risks on the SCD and the selection of suppliers. By introducing varying uncertainty levels into the initial risk assessment, it will be possible to study their impact on the SCD. We will study they affect the size of supplier modules, as well as the optimal sourcing flexibility. In practical terms, scenarios produced through higher uncertainty levels represent more pessimistic scenarios, meaning that the suppliers' performance deviated considerably from the original assessment.

3 The Value to Society

The Aerospace Sector has changed considerably in the wake of catastrophic events and OEMs have adapted both their products and supply chains to respond to market pressures. This rapid evolution has led to a series of sources of uncertainty that must be considered in the design of supply chains for new aircraft programmes. OEMs are prioritising the reduction of final assembly times and have requested larger sections to be integrated by key suppliers.

Supply Chain Design under supply chain risk management has been vastly explored by academia. The existent literature describes various methodologies to analyse sources of uncertainty for different industries. The contribution of this paper is threefold: first, it addresses an undocumented industry within the scope of Operations Management. Second, it studies emerging sources of risk which have led to unforeseen expenses and delays in recent aircraft programmes. Third, it employs a unique approach to robust optimisation focusing on SCD.

The goal of this research is to make aerospace SCD more robust towards emerging sources of risk. The conclusions drawn from this research will support decision makers in designing supply chains for future aerospace products that mitigate the uncertainties that threatened previous programmes.

We model the trade-off between supplier modularity and integration risk. We analyse how the risk aversion of OEM decision makers affects the robustness of SCD. We model propensity for merger between key suppliers and the impact of these decisions on the supply chain. Robust optimisation is used to investigate how supplier modules should be assembled to achieve stable SDC. We propose strategies to mitigate integration and consolidation risks is studied through different levels of sourcing flexibility and by adjusting the integration assigned to supplier modules.

Appendix C

IEMS '21 |

Extended Abstract:
12th Industrial Engineering and Management Symposium

The Impact of Sustainable Aircraft Specifications on Airline Fleet Planning

Nuno Falcão e Cunha[*†] · **Pedro Amorim**[*†] · **Bernardo Almada-Lobo**[*†]

1 The Challenge

The aviation sector is highly susceptible to global political, economic, and health circumstances. In 2001, the September 11 attacks demanded an unprecedented overhaul across the entire industry. The expensive security protocols and loss of passenger trust forced airlines to lower their operating costs. This also pressured OEMs to improve their aircraft and their supply chains. In recent years, $C0_2$ emission and sustainability objectives motivated the interface between these agents.

In 2019, the global aviation industry was responsible for 12% of $C0_2$ emissions from all transport sources, whereas road transport accounts for 74%. However, aircraft travel averages nearly seven times the emissions in grams of $C0_2$ per passenger per kilometre. In total, this industry also accounted for 2% of human-induced emissions. Faced with these numbers, through the ATAG, the aviation industry announced its goal of halving $C0_2$ emissions by 2050, compared to the ones measured in 2005. The ATAG also committed to halt

*INESC TEC - Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência, Porto, Portugal
† Faculdade de Engenharia, Universidade do Porto, Porto, Portugal

the rise of net emissions by 2020. Even though the COVID-19 pandemic led to an abrupt decrease of these emissions, this effect is temporary and current reports suggest a return to the 2019 air traffic by 2023. As more aircraft take to the skies, the challenge remains of optimising individual aircraft efficiency.

The pursuit of these goals comprises three strategic axes: innovation in aircraft and engine design, promoting the use of alternate fuels, and the emergence of a new generation of aircraft with disruptive propulsion technology. Over the past few years, OEMs in this sector have introduced key technological innovations such as advanced aerodynamics, more sophisticated avionics, and the introduction of winglets, which reduce fuel consumption by up to 6%. The emergence of composite materials was one of the most disruptive innovations for the aviation industry. In the past, aircraft were made of up to 70% aluminium. Nowadays, in aircraft such as Boeing's B787 and Airbus's A350, composites account for over 50% of their structural weight. The most evident benefit of these materials is the weight reduction and ensuing gain in fuel efficiency. Furthermore, they are not susceptible to corrosion and are more resistant to impact, thus reducing maintenance costs.

Notwithstanding the commitment made by agents across the entire industrial sector, airlines are faced with a difficult trade-off between sustainability practices and their passengers' interests. In fact, during fleet selection and management decisions, airlines combine criteria from multiple domains. On one hand, airlines seek to minimise $C0_2$ emissions, fuel consumption, maintenance requirements, and even noise. On the other, when assigning an aircraft to a route, they must look at seat capacity, maximum take-off mass, and aircraft range.

This work aims to measure how individual aircraft attributes correlate to their demand, and assign to each of them a market share contribution. Analysing yearly purchases made by international airlines will also establish how the weights of these priorities have evolved. This survey will highlight whether airlines prioritise sustainable attributes over financial and route-specific considerations. A by-product of this analysis is a market share predictor for new aircraft, according to its specifications. This will simultaneously forecast its potential demand, but also which existent aircraft stand to lose market share from direct competition.

2 The Methodology

Currently, there are over three thousand airlines operating around the world. This analysis is restricted to the top one hundred ranked airlines in the world, according to Skytrax. This includes twenty low-cost airlines. This organisation counted over twenty-one million surveys and identified the best airlines both in terms of the maintenance levels of their aircraft, but also the quality of their services. This range of airlines was chosen both due to the necessity to limit the data set, but also since this is likely a good indicator of the airlines with the best fleet management practices. Using open-source databases, data on current and historical fleets since the inception of these companies was gathered. This data includes over thirty thousand transactions of new and used aircraft, with seventy-one unique aircraft models, and ensuing sub-models. For each aircraft entry, the information compiled includes its manufacturer, model, and date of purchase. The regression model employed to process this data estimates the different utilities for new and used aircraft, as perceived by the airlines, in each acquisition.

For all aircraft models listed across these companies, a comprehensive list of specifications was assembled, as per the ones advertised by their OEMs. This included information on sustainability-oriented specifications such as fuel burn per kilometre per person, wingtip configuration, percentage of composite materials, and noise levels. Furthermore, the list compiles operational specifications such as seat capacity, maximum payload, maximum range, cruise speed, and fuel capacity. In line with the objective of this study, some of these criteria can be related to environmental sustainability, whereas others are linked to business or financial planning.

As stated above, a nested logit demand model is used to understand how individual specifications impact the probability of an airline choosing to acquire an aircraft. In this setting, airlines are said to make decisions that maximise utility. This utility is defined as a linear function of each aircraft's complete set of attributes, as well as non-tangible airline-specific preferences. The regression within this discrete choice model determines the perceived utility of each aircraft for each airline. This makes it possible to estimate relative utilities for the aforementioned range of attributes. Furthermore, by defining calendar years as different time periods in the regression, it is possible to observe how these utilities evolved over time, and whether sustainability metrics are indeed becoming more relevant. The logit demand model also predicts aggregated market share for an aircraft, based on its attributes.

The nesting within the model distinguished wide-body and narrow-body aircraft, as well as new and used aircraft. For the one hundred airlines under scrutiny, two additional discriminators are applied. First, whether the airline is a continental or global operator. Second, whether they are low-cost airlines or not. This will provide insight into how fleet management practices vary with the success of the company and its business plan. There is also the possibility of analysing the relative utilities of aircraft specifications for airlines across different geographic regions.

3 The Value to Society

As the discrete choice model indicates the most sought-after attributes, OEMs are provided with straightforward indicators for the development of new aircraft. They may also gauge the expected aggregate market share of aircraft projects they have in the pipeline. Since each aircraft generation must stay in the market for at least fifteen to twenty years, due to the high non-recurring costs, maximising market adoption is a valuable prospect.

The high costs involved in adapting and maintaining their fleets make resilient strategic planning fundamental for the success of all airlines. After overcoming the challenges posed in 2001, the industry shifted to comply with environmental standards. However, 2020 brought an even bigger challenge, the COVID-19 pandemic, which grounded nearly seventy percent of the global fleet between January and April. Airlines must ensure long-term sustainability of their fleets as they reactivate their services. It is clear that airlines had heterogeneous fleet planning practices in the past. By looking at the most successful profiles as the perceived utility of certain aircraft characteristics evolved, it may be possible for airlines to improve their future practices.

For the members of the ATAG group, as well as for society in general, this analysis will lay out the market's interest in pursuing their environmental sustainability target. It will weigh whether attributes directly linked to sustainability or route-specific considerations are more important in fleet management practices. This doesn't mean that companies disregard their sustainability goals, but they may be forced to choose faster or larger planes to fulfil customer demand. Especially in the wake of disruptive events that put pressure across all the nodes within the industrial sector, priorities must be clearly outlined. This is the only way suppliers, OEMs, airlines, and airports can come together to ensure the recovery of the sector.