Sustainable Supply Chain Optimisation Model: the case of a Composite Aircraft Structure

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"Imagination is more important than knowledge.

For knowledge is limited, whereas imagination embraces the entire world (...)"

Albert Einstein

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Abstract

Use of composites in aerospace has been increasing regardless of prohibitive costs of material, development and manufacturing. In an industry defined by global, complex networks of partners-suppliers that work symbiotically to develop high-value long-lasting products, every single improvement is critical. Growing air traffic and increasing backlogs suggest higher pressures on the industry and supply chains, demanding additional coordination effort of these networks.

In this research, a state-of-the-art review is carried out on the topics of the aerospace industry, advanced materials, product development, supply chain management, optimisation and modelling techniques, and sustainability issues.

A Mixed-Integer Programming model is proposed to aid on decisions of global network supply chain design for Carbon Fibre-Reinforced Polymer manufacturing in aerospace industries. In general, the model considers a (1) superstructure of entities and locations, a (2) transportation network, the (3) distance between all entities/locations, a (4) set of resources, materials, technologies and time constraints, and respective manufacturing needs, (5) a set of alternative processes, and the (6) economic, social and environmental impacts of all of decisions. This model is based on sustainable performance measures, thus aiming at maximising economic return, and minimising environmental and social impacts. The case of Embraer is presented and four forming processes are compared.

Among other conclusions, further study is recommended for the adoption of VBO as a promising technology that meets economic performance standards comparable to those of TA and factors like batch size, scale-up, demand and part length have great impact on this recommendation.

Keywords: Aerospace, Supply Chain, Optimisation, Sustainability, Composites, New Product Development.

Resumo

Embora no caso de compósitos os custos de material, desenvolvimento e fabricação sejam proibitivos, o seu uso na aeronáutica tem aumentado. Numa indústria definida por redes globais e complexas de parceiros-fornecedores, que trabalham em simbiose em produtos duradouros e de elevado valor acrescentado, cada melhoria é essencial. O aumento do tráfego aéreo e encomendas sugerem pressões nestas redes, exigindo esforços de coordenação acrescidos.

Nesta pesquisa, é realizada uma revisão da literatura sobre a indústria aeroespacial, materiais avançados, desenvolvimento de produto, gestão da cadeia de abastecimento, técnicas de otimização e questões de sustentabilidade.

Um modelo de Programação Linear Inteira Mista é proposto para o planeamento da cadeia de abastecimento para a produção de polímeros reforçados com fibra de carbono. O modelo considera uma (1) superestrutura de entidades e localizações, uma (2) rede de transporte, a (3) distância entre todas as entidades/locais, um (4) conjunto de recursos, materiais, tecnologias e restrições de tempo, e respectivas necessidades de produção; (5) um conjunto de processos alternativos; e (6) impactos económicos, sociais e ambientais de todas as decisões. Este modelo baseia-se em medidas sustentáveis, visando maximizar o retorno económico e minimizar os impactos ambientais e sociais. O caso da Embraer é apresentado e quatro processos de conformação alternativos são comparados.

Nas conclusões, recomenda-se o estudo aprofundado para a adoção do ’vacuum-bag’ (VBO) como uma tecnologia promissora que apresenta desempenho económico comparável ao Autoclave (TA) e fatores como tamanho de lote, aumento de escala, procura e tamanho da peça têm impacto nesta recomendação.

Palavras-chave: Aeronáutica, Cadeias de Abastecimento, Otimização, Sustentabilidade, Materiais Compósitos, Desenvolvimento de Novos Produtos.

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Acronyms

CO_2**e** Carbon Dioxide equivalent
3BL Triple Bottom Line

ABC Activity-Based Costing
ACCEM Advanced Composites Cost Estimating Manual

BOM Bill of Materials

CAD/CAM Computer Aided Design/Manufacturing
CER Cost Estimation Relationship
CFRP Carbon Fibre-Reinforced Polymer
COSTADE Cost Optimisation Software for Transport Aircraft Design Evaluation

EU European Union
EUR Euro

GDP Gross Domestic Product
GHG Green House Gas

IAMAT Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries
INEGI Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (Institute of Science and Innovation in Mechanical and Industrial Engineering)

KPI Key Performance Indicator

LCA Lifecycle Assessment
LCC Lifecycle Costing
LP Linear Programming
LSSI Large Scale Systems' Integrator

MILP Mixed-Integer Linear Programming
MIP Mixed-Integer Programming

NDT Non-Destructive Testing
NPC Net Present Cost
NPD New Product Development
NPI New Product Introduction
NPV Net Present Value

OEM Original Equipment Manufacturer
OoA Out-of-Autoclave
OR Operations Research

R&D Research and Development
RDTE Research, Development, Testing and Evaluation

RTM Resin-Transfer Moulding

S-LCA Social Lifecycle Assessment
SC Supply Chain
SCM Supply Chain Management
SSCM Sustainable Supply Chain Management

TA Traditional Autoclaving
TQM Total Quality Management
TS Thermo-Stamping

UK United Kingdom
US United States
USD United States Dollars

VARI Vacuum-Assisted Resin Infusion
VBO Vacuum-Bag Only

WBS Work Breakdown Structure
WW World War

1 | Introduction

This chapter aims to provide an outline of this Master's dissertation, with background and motivation for the problem at hand, including the definition of scope and objectives of this research. In spite of being concise, the chapter is divided into three parts for easier understanding. The first part presents the background and context of the problem. The second section of this chapter introduces the problem and the objectives that are to be attained, along with the structure to be followed by the document. The third and last section presents the methodology adopted for the research.

1.1 | Background and Motivation

The airline industry as is known today owes much to the Convention on International Civil Aviation (held in Chicago in 1944), which outlined the international rules for aviation that aimed to increase safety and security. These rules shaped airline operations, both international and domestic, paving the way for the first set of global standards of the industry. The tragic events of September 11, 2001, have also changed the industry of air transportation, resulting in increased security procedures to ensure the safety of passengers and cargo (Febeliano, 2008). From 1944 on, the airline industry has undergone many changes, especially in what concerns business models. Throughout the '60s, air travel was a remarkable event and object of desire for most of the middle class. These traditional network carrier (or full-service network carrier (FSNC)) business models were challenged by the low-cost carrier (LCC) business models, more focused on serving the simple, short-haul passenger demand. LCCs have turned air transportation into the so-called ultimate commodity, enabling the democratisation of air travel (Tretheway, 2004; Nairn, 2005). It led to the increase in traffic and triggered many changes in the typical airline processes and operations. Airlines tried to combine low-cost strategies with additional, complementary offerings on what is called hybrid business models (Tretheway, 2004).

Nowadays, aviation and related activities are a driver for growth and skilled employment. The figures speak for themselves: a total of 900 airlines worldwide, a combined fleet of nearly 22,000 aircraft serving around 1,670 airports, managed by approximately 160 air navigation service providers yield an overview of the impact of air transport (ATAG, 2005; European Commission, 2011). For future reference, air transport industry is a general concept that includes the aviation industry (e.g., airlines, airport management, air navigation services) and the aerospace industry (e.g., airframers, engine or avionics manufacturers). As of 2005, the air transport industry generates 13.5 million jobs - of which 5 million are direct jobs -, without mentioning other activities supported by air travel (e.g., tourism) (ATAG, 2005). In Europe alone, air transport can generate 4.5 million jobs, adding 220 billion € to Gross Domestic Product (GDP). European integration and cohesion are also strongly affected by air travel (European Commission, 2011).

According to IATA's Fact Sheet and Statistics 2017, there has been a consistent growth in air transportation demand, for both passenger and cargo traffic flows. Even though, there is not a linear correlation between traffic growth and the profit generated by the activity of airliners. Operational costs (especially those related to fuel) are a great barrier to growth and profitability, resulting in increased interest for lightweight aircraft. This higher demand has been defying the aerospace industry and aircraft manufacturers, driving the development in the field of new and advanced materials (Richter and Witt, 2017). Even though the aerospace industry is not the only industry that requires new materials, it is the central focus of IAMAT (2017).

1.2 | Problem Statement, Objectives and Outline

This dissertation is an integral part of a more comprehensive and extensive research endeavour, Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries (IAMAT). The research group includes an industrial partner - Embraer - and several research partners - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (Institute of Science and Innovation in Mechanical and Industrial Engineering) (INEGI), University of Porto and University of Minho. As the project name suggests, the research aims to study the implications of introducing new materials onto an existing Product Development process, in the particular case of the aerospace industry (IAMAT, 2017). More specifically, this dissertation is focused on the problem of the influence of these new materials in the Supply Chain (SC) of the aerospace industry.

Regarding the dissertation's research problem itself, it is believed that there is a gap in the literature concerning sustainable Supply Chain (SC) optimisation models specifically designed for the aerospace industry under conditions of new materials introduced into the Supply Chain (SC). For this reason, a consistent literature review of the relevant topics, namely the aerospace industry, advanced materials, cost modelling, supply chain management, product development and sustainability is developed to confirm or disprove the existence of such research gap. For this purpose, the following research goals are stated:

- Getting to know the aerospace industry and supply chain, along with its characteristics and specific issues;
- Understanding the benefits, properties, disadvantages and applications of advanced materials;
- Extending knowledge of modelling, formulation and implementation of mathematical models dedicated to the supply chain;
- Contributing to the academic community and taking responsibility for carrying out a research task;
- Helping to solve the problem identified so that the technology becomes more affordable;
- Developing the set of skills associated with typical research problems and research methodology.

The primary goal of this Master's dissertation is to help closing the identified research gap for sustainable Supply Chain (SC) optimisation models designed for the aerospace industry that account for the introduction of these new materials. The research question linked to this is to find out which manufacturing process should be adopted by the aerospace industry for composite Carbon Fibre-Reinforced Polymer (CFRP) parts, based on sustainable performance measures. Emphasis is put on Out-of-Autoclave (OoA) technologies as potential cost reduction factors and comparison with existing technologies. Aligned with Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries (IAMAT) on the pursuit of a framework to evaluate and decide on the appropriate process, only four forming processes are considered: (1) Traditional Autoclaving (TA), (2) Vacuum-Assisted Resin Infusion (VARI), (3) Vacuum-Bag Only (VBO) and (4) Thermo-Stamping (TS). By undertaking a holistic approach not focused only on economic measures but also environmental and social - and after proper application to a testbed -, it is intended that this framework can be generalised to other mobility industries.

For easier reading of the dissertation document, it is important to outline the adopted structure. All chapters begin with a brief introduction and end with a few words which summarise its content. In between, several sections are used to divide the information into smaller portions making it easier for reading and a better understanding of the different matters discussed. In order to attain the above-stated objectives, this dissertation is structured as follows:

- **Chapter 1 - Introduction:** The background and context for the research problem, its objectives and the actual structure of the dissertation are introduced.
- **Chapter 2 - Aerospace Industry:** The central topics of the aerospace industry are presented, such as key concepts, main problems and characteristics. The topics of the aerospace supply chain, product lifecycle and new product development are reviewed.
- **Chapter 3 - Literature Review:** The literature is reviewed on the most relevant topics for the research, in order to build foundations to understand the problem better. Therefore, the topics of advanced materials and their manufacturing processes, cost estimation models and topics related to supply chain management are addressed.
- **Chapter 4 - Problem Definition and Formulation:** This chapter describes the problem and provides context for development of the referred sustainable SC optimisation model for the aerospace industry. A model framework is presented and the model objectives are also explained.
- **Chapter 5 - Case Study:** This chapter provides an instance for model's testing. Necessary underlying assumptions and simplifications are provided, and several summary tables are presented with case study's data. All information collected to feed the optimisation model is presented in this chapter and summarised in tables.
- **Chapter 6 - Case Study Results and Discussion:** This chapter details the computational experiments and discusses the main results and findings of this research, through the implementation of the optimisation model.
- **Chapter 7 - Conclusions and Future Work:** This last chapter discusses and summarises the main points from the dissertation and provides final remarks on the more relevant findings.

1.3 | Methodology

The fundamental research aim is to develop a model for aerospace composites manufacturing and supply chain. Primarily, it is necessary to understand all topics linked to the central problem, through a proper problem characterisation. Moreover, it is essential to develop the skillset for the construction of such a model, which is accomplished through a comprehensive literature review. Particular attention is devoted to the scale-up and ramp-up processes since the model needs to represent the reality currently being studied in a testbed. Figure 1.1 describes the methodology applied in this Master's dissertation.

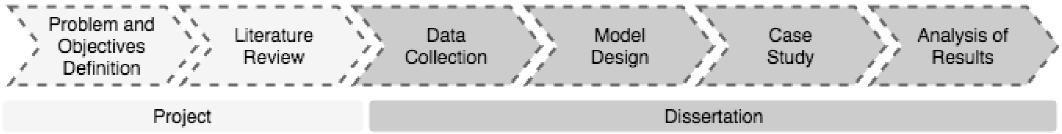

Figure 1.1: Steps of the research methodology.

The adopted research methodology for the modelling process involves six main steps: study the problem and context and define objectives, collect data, develop the model, validate with a case study and analyse results.

- **Step 1 - Problem and Objectives Definition:** This step studies and introduces the background and context for the research problem, as presented in Chapter 1.
- **Step 2 - Literature Review:** This step aims to build a holistic perspective of the research and its related fields. The literature review is mostly based on books, journals, reports, theses and other academic sources. This literature is specialised on the topics of aerospace industry, advanced materials, product development, supply chain management, optimisation and sustainability. The result is the report presented in Chapters 2 and 3 of this document.
- **Step 3 - Data Collection:** Step 3 aims to gather the necessary data for the modelling step. Hence, information regarding materials, manufacturing processes, labour, equipment and transportation modes. This data collection resorts to literature, industrial players and other appropriate sources available.
- **Step 4 - Model Design:** The step 4 is where all data and knowledge from the literature are combined to give origin to a mathematical model for optimisation of the supply chain. The output of this step is a reusable and parametric model and this is described in Chapter 4.
- **Step 5 - Case Study:** The model is validated via application to a case study, plugging information from real industry players. This step is essential to evaluate if the model is both representative and concise.
- **Step 6 - Analysis of Results:** Being the final step of the research, the results obtained and the main conclusions are discussed. In addition, work limitations and suggestions for future work are presented.

2 | Aerospace Industry

Chapter 1 presented a brief description of the research motivations and what is aimed to be achieved. The present chapter introduces the reader to the aerospace industry: concerns, specificities and key concepts in related literature. Readers unfamiliar with aerospace and connected terminology should be able to understand the results and conclusions fully. For this purpose, the chapter is divided into four sections.

The first section provides basic information and lays the foundation on which the remaining sections build their narrative. It should provide answers to questions related to main players, products and general status of the industry. The second section discusses the Aerospace Supply Chain since the purpose of the research is to develop a model for SC optimisation. Section three presents the Product Lifecycle, so that previous and subsequent phases besides the aircraft's operation are also understood. Last section condenses all the learning outcomes that are relevant for understanding the rest of the document. A brief notion of what is to be discussed in the next chapter is also provided, bridging the two main pieces of the literature review.

2.1 | Characterisation of the Industry

Some aspects set the aerospace apart from other industries. One that immediately comes to mind is the low volume production of many different parts. Other examples are the product and programme lifecycles of 30 or more years, the entanglement of design and assembly of 2 to 4 million parts for one aircraft, the strict specifications for product safety and reliability, and the global, highly specialised and fragmented supply base. All these features combined with strong and lasting dependencies between companies define some of industry's specificities (Mundt, 2003; Chang, 2006). In terms of product innovation, aerospace can be considered a "slow-motion sector' with a rate of new product launch of about two aircraft per decade (Niosi and Zhegu, 2008).

The market segments in commercial aviation are Large Commercial Aircraft, Regional Jets, Business/Executive Aviation and Defence Aviation. There are few players in each segment due to prohibiting entry barriers - mostly in terms of first-class knowledge, high-end technology and capital requirements - but it is still a very competitive environment (Niosi and Zhegu, 2005*a*; Ibsen, 2009). Some players are even present in the segments of Helicopters and Space, but these are out of the scope of this research. Niosi and Zhegu (2005*a*) identify Airbus and Boeing as the leading Original Equipment Manufacturers (OEMs) for planes over 100 seats (the segment of Large Commercial Aircraft), while Bombardier and Embraer dominate the segment under 100 seats (Regional and Executive Jets). Even though, as Clearwater (2011) writes, the gap between these two markets has been tightening, with manufacturers of small-sized aircraft trying to overlap the lower-sized product offerings of bigger OEMs. The cases of Embraer's E2 series, with potential capacity for over 140 passengers, and Bombardier's C-Series, with up to 160 seats, are examples of this. It is also important to distinguish between narrow-body (single-aisle cabin) and wide-body (twin-aisle cabin) aircraft, the configurations of which can be defined according to the customers (usually airlines, freight companies or States). ICAO (2004) defines wide-body as large transport aircraft with passenger seats arranged in three axial groups divided by two aisles (total width greater than 4.72 meters), while in a narrow-body airliner the passengers are seated in two groups separated by one aisle. This classification scheme does not invalidate that aircraft are used for purposes other than passenger transportation since almost any configuration is possible.

In their market forecast for the next two decades, Airbus (2017), Embraer (2017*b*) and Boeing (2017) expect a passenger traffic average annual growth of 4.4% to 4.7%, proving resilience to adverse economic conditions. Bombardier (2016) does not report projections for traffic growth but endorses that same trend. This stable, growing traffic has increased the demand for aircraft, and airlines are renovating and enlarging their fleets, hence challenging OEMs to 'unprecedented production ramp-ups'. Airbus (2017) expects demand for 34,900 new aircraft, of which 40% is due to fleet replacement and 60% come from net growth, Boeing (2017) anticipates more than 41,000 deliveries, and Embraer (2017*b*) foresees to have delivered 6,400 new jets by 2036, similarly split. A large part of the sales is of passenger aircraft rather than freight, and narrow-body types are predicted to have higher demand than wide-body. Business-focused aviation's Bombardier (2016) forecasts 8,300 deliveries from 2016 to 2025, whose North America and Europe being the most significant markets.

The magnitude of backlogs is also pushing OEMs to "achieve a shorter time-to-market" and to find new ways of increasing production throughput (Treuner et al., 2012). Whether it is a private or public entity, seeking profit maximisation or operation cost reduction, the ultimate goal of air carriers is to make efficient use of each aircraft, matching capacity to demand (ICAO, 2004). Thus, with the increase in jet fuel prices, air carriers look to reduce the one which is the largest single component of an airline cost structure: fuel (Richter and Witt, 2017). As a result, OEMs need to adapt to market forces constantly. Not only the fuel prices, but also economic development, regulations, infrastructure, liberalisation, aircraft capabilities, other means of transportation, customers' business models, tourism development, and emerging markets (Boeing, 2014, 2017; Airbus, 2017). Airlines' business models sustained on low-cost product offerings and the increase of traffic in developing countries are examples of the trends that are shaping the industry (Richter and Witt, 2017).

The evolution of the aerospace industry can be divided into four periods. Boeing's foundation, in 1916, up until the end of World War (WW) II, around 1945, marks the first period and corresponds to the United States (US) monopoly, with nation-spread SCs and national market protectionism regulations. From the 1960's on, the second period is characterised by Europe growing its aerospace market and production capabilities. Due to the lack of capabilities of individual countries, international cooperation with others had to be developed, having France and Germany as the main cast for this consortium. Then followed the duopolistic "war between Airbus and Boeing" in the 1970's, which marks the third period, boosting the competition in aerospace (Horng, 2006). The last period spans until today, the industry being globalised and both major players having stable market shares (Niosi and Zhegu, 2005*a*; Richter and Witt, 2017).

The industry is now global, and there are several reasons pushing internationalisation based on market, cost, government or competitive drivers (Johnson et al., 2014). Emiliani (2003) mentions lowering recurring costs and increasing market as the key drivers for such globalisation. In spite of the global SC, there are regions with dense aerospace production environments, as this industry is characterised by local and regional clusters. Niosi and Zhegu (2005*a*) identify major aerospace clusters in US and Europe: Los Angeles, Seattle, Washington (US), Bristol, Lancashire (United Kingdom (UK)), Toulouse, Bordeaux (France) and Bavaria, Hamburg (Germany).

There are other explanations for both regional concentration and global expansion, but the main ones are of historical and political nature. The use of offset agreements is a mechanism that has been increasingly used, as governments leverage the investments on aircraft and airlines' fleets as a mean to impose conditions to OEMs. Typically, governments demand the development of aerospace capabilities in their countries (Brazil, China, India and Korea, for instance) (Emiliani, 2003; Niosi and Zhegu, 2005*a*).

Finally, it is worth mentioning that this industry is highly dependent on government funds due to high and rising development costs. It may require up to 500 units sold for an aircraft to be profitable, so the payback periods are very long (Mowery and Rosenberg, 1989; Niosi and Zhegu, 2008). Research and Development (R&D) and manufacturing are expensive and knowledge-intensive steps. In this high value-added industry, transportation costs during the manufacturing process are deemed irrelevant for the overall aircraft cost (Niosi and Zhegu, 2005*a*).

Besides benefiting from fast technological development and government-funded R&D, this industry is characterised by global customer markets and an increasingly global supplier base, leading to long and complex networks. For this reason, Supply Chain Management (SCM) is a matter of great concern for aerospace players. The next section presents the concepts, different models, concerns and issues related to the aerospace SC.

2.2 | Aerospace Supply Chain

APICS (2017) defines SC as "the global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash". Harland et al. (1999) and Ayers (2001) add the notion of customer requirements and satisfaction, and the connection between multiple suppliers. As for Simchi-Levi et al. (2004), SCM is the "set of approaches used to efficiently integrate suppliers, manufacturers, warehouses, and stores so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time [to] minimize system-wide costs while satisfying service-level requirements".

As studied by Bozdogan et al. (1998) and Niosi and Zhegu (2005*a*,*b*), this industry spanned across many countries with both local and global focuses. The pace of changes in business environments, including demand and technology evolution, force the SCs to readjust to each specific context (Harland, 1996; Rose-Anderssen et al., 2011). Several were the SC strategies adopted by each player over the years to beat the competition, prompting the classification and study of the main steps of this evolution by different authors (Higham, 1968; Gostic, 1998; Rose-Anderssen et al., 2011). The aerospace SC is global also due to the strategic sourcing strategies that the industry has been pursuing. Fig. 2.1 presents the frontiers and the timeline of aerospace sourcing strategies that dictate different structures of the SC. From there, it is possible to notice the move towards supplier-buyer relationships (Chang, 2006).

In the 20th century, OEMs were using in-house production and carrying inventories, and the relations with suppliers were just transactional and circumstantial (Higham, 1968; Bales et al., 2004; Rose-

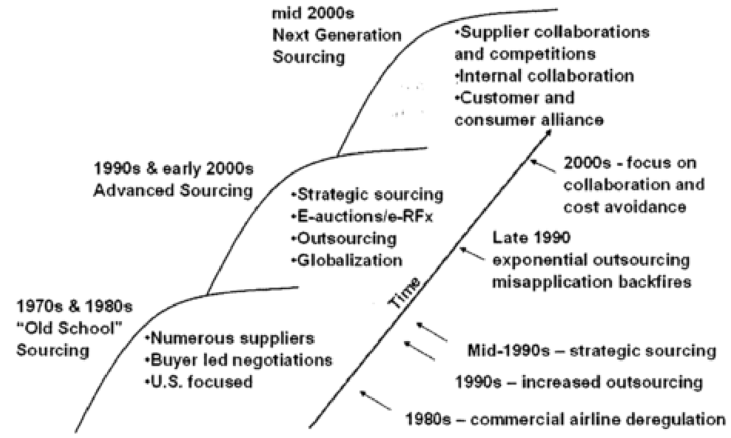

Figure 2.1: Timeline of aerospace sourcing strategies. Source: Chang (2006).

Anderssen et al., 2008, 2011). Even though they had a higher degree of control over the operations and the core capabilities, they were also more exposed to risk (Williams et al., 2002; Rose-Anderssen et al., 2011). The aerospace industry had a strong regional and clustering association, especially by the beginning of WW I. After WW I, in 1918, OEMs maintained an arm's length relationship with suppliers selected according to price criterion (Bales et al., 2004; Rose-Anderssen et al., 2008). From WW II on, the first efforts for collaborative SCs began to appear. During the 1970's, American companies still followed an OEM-led strategy, maintaining in-house manufacturing activities, when the foundation of Airbus forced the industry to adapt and evolve continually (Higham, 1968; Rose-Anderssen et al., 2011). The industry went through antagonistic periods of strong vertical integration (a diversification strategy to spread risk and acquire capabilities) and 'vertical disintegration' (to reduce supplier base and focus on core operations) (Harland, 1996; Gostic, 1998; Johnson et al., 2014). Borrowing the evolutionary approach from biological sciences, Rose-Anderssen et al. (2008) performed an exhaustive classification of the SC strategies adopted by OEMs. Some examples of these strategies are joint ventures and Total Quality Management (TQM), agile and lean SC, or the different approaches of global SC.

From their partnerships with customers for New Product Development (NPD), OEMs started to develop deeper connections with first-tier suppliers to gain access to markets, capital and technology. These risk-sharing strategic alliances also benefit the suppliers since they can guarantee long-term business transactions and gain knowledge that OEMs may provide (Rose-Anderssen et al., 2008; Martinez, 2007). Suppliers followed similar approaches to their own suppliers and companies started to look globally for the best risk-sharing partners that would be able to share the financial burden of developing an aircraft programme. Modularisation of aircraft and low throughput enabled OEMs to outsource complete subsystems (Niosi and Zhegu, 2008). With the aim of cost-effectiveness and focus on core competencies, OEMs externalise the production and outsource most activities to suppliers (such as engines, aerostructures and avionics) (Niosi and Zhegu, 2005*a*). In this type of relations, OEMs cease manufacturing functions and become 'large-scale integrators' (Rose-Anderssen et al., 2008). This evolution is depicted in Fig. 2.2.

The Large Scale Systems' Integrator (LSSI) is strongly supported by strategic alliances, where the

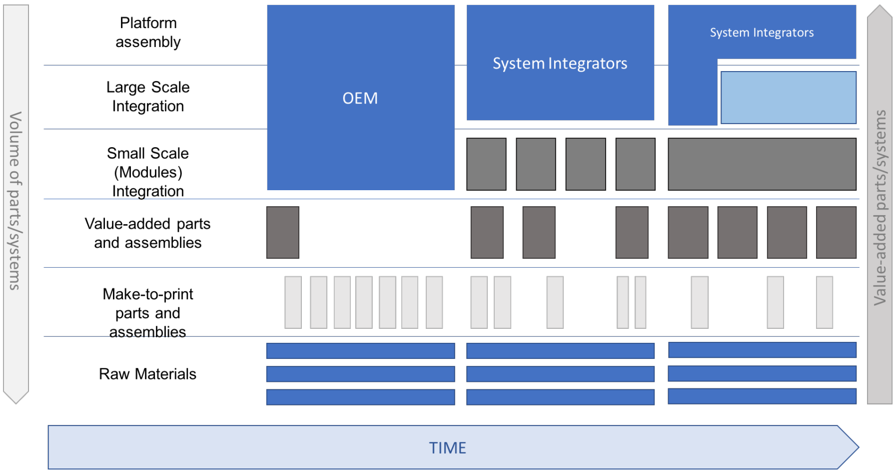

Figure 2.2: Evolution of aerospace supply chains. Adapted from SBAC and ATKearney (1998).

OEMs' sole focus is on their core competencies and whose outsourcing would constitute a significant risk for them. Guerra (2011) proposed marketing and sales, product development, final assembly and delivery as the OEMs' core competencies; in order words, all tasks related to the customer relationship. Tier 2 includes aerostructures, engine and avionics manufacturers, and tier 3 produces related sub-assemblies. Other small and medium manufacturers integrate the aerospace SC (tier 4), producing parts and components for all the tiers above but also for other industries (Niosi and Zhegu, 2005*a*).

Petrick (2007) shows that the influence of tier 2 and tier 3 suppliers increases when LSSI models are used, shifting from the OEMs and tier 1. As these become more powerful in the SC, there is the need to invest more in innovation and development of capabilities. The classification scheme of suppliers proposed by Petrick (2007) is useful for understanding their relative importance across the SC, starting with the commodity suppliers (e.g., machined parts), followed by the value-added suppliers, the strategic suppliers and (the most influencing) key collaborators.

Moreover, offset agreements have characterised the aerospace history for many years now, with governments binding the collaboration of OEMs with their national institutions. These agreements have been driving forces of strategic alliances (National Research Council, 1999; Martinez, 2007). Access to specific technologies or qualified companies, offset agreements and reduction of risk/barriers are among the common motivations for using the systems' integrator model (Guerra, 2011).

The literature from strategic management (Johnson et al., 2014) recognises strategic alliances as means of extending capabilities and competitive advantages where both risk- and resource-sharing are key. A strategic alliance can be defined as a partnership of organisations to pursue a common strategic goal. This is the strategy to follow if OEMs aim either diversification of their business, internationalisation or innovation, without the added complexity and risk of ownership associated with vertical integration. Main reasons for these alliances are to increase capacity without significant investments, access to specific capabilities or knowledge and enter markets otherwise inaccessible for political reasons (Johnson et al., 2014).

According to Treuner et al. (2012), global and complex SCs with many outsourced functions are more exposed and vulnerable. Some causes for disruption are resource constraints, communication issues and supplier solvency. The author refers that only 9% of disruptions are due to internal issues in the SC, as opposed to the 91% that occur upstream. Pressure from customers and the need for higher production rates made OEMs adopt extreme strategies that led to SC disruption events (Funo et al., 2013) . Some examples were the cases of Airbus, with the production of the A380, and of Boeing, with its 787's programme, the latter being well-known for the successive delays (Treuner et al., 2012).

Tsay (2014) presented the case study of Boeing 787 programme, a famous example of lack of capabilities and skills from suppliers, poor quality assurance, unauthorised subcontracting, coordination issues and 'loss of critical skills'. Failures gained more relevance especially due to the value proposition of a product capable of fuel efficiency and maintenance savings, leading to the unique number of orders from airlines (up to 900 orders before the first flight) (Tang et al., 2009; Zhao, 2012). The first delivery was delayed in 3.5 years with budget overruns from \$12 to \$18 billion United States Dollars (USD) over the initial estimate of \$5 billion USD (Guerra, 2011; Gates, 2011).

This case study is particularly relevant as 787 was regarded to be the first large commercial aircraft with various structural applications of composite materials (Tang et al., 2009; Tsay, 2014). Boeing adopted an aggressive 'Tier 1' model, sharing the 'wrong-risk' with suppliers that resulted in unclear responsibilities. Disruption risks can be avoided or mitigated through appropriate supplier selection, well-sustained partnerships and close monitoring of suppliers. A reliable supply alliance network, the reduction of lead times and a recovery planning systems are essential as risk mitigation strategies (Tang, 2006; Zhao, 2012).

Having presented the main topics of aerospace SCs it is relevant to understand how the different stages of product lifecycle relate to the SC. As the two dimensions are tightly linked, product lifecycle is introduced and discussed in the next section.

2.3 | Product Lifecycle

As the name suggests, product lifecycle is the sequence of phases that are part of the product's life, from the conceptual idea to the final disposal. The industrial product lifecycle should not be confused with the lifecycle of a product in the market. The latter is a marketing concept that includes four stages (introduction, growth, maturity and decline) of a product as a function of the sales volume (Rink and Swan, 1979). Alting (1991) defined six different phases, starting with (1) need recognition, (2) design/development followed by (3) production, then (4) distribution and actual (5) usage, and finally (6) disposal/recycling. Later, Kriwet et al. (1995) proposed a system lifecycle composed of the cycles of three different elements: product, associated processes and logistics (Fig. 2.3).

Based on product lifecycle details, Lifecycle Costing (LCC) is an essential framework for cost estimation. For instance, it enables OEMs to define an initial price for the products to be validated by customers (White and Ostwald, 1976; Asiedu and Gu, 1998). Some research suggests that product design may influence up to 85% of the total cost, with impact on all the subsequent phases; hence the vital part played by design engineering. Interestingly enough, as the design freedom and possibility of changes decreases, the knowledge about the design problem increases; this is usually called the knowledge/freedom paradox (Asiedu and Gu, 1998; Dieter and Schmidt, 2009). Similarly, Lifecycle Assessment (LCA) is a tool to evaluate the impacts of products on the environment with the goal of ensuring sustainability across the cycle (Asiedu and Gu, 1998). This topic is closely linked to the discussion of sustainable SCs. Both topics will be detailed in the next chapter.

In aerospace industry, all these steps of the lifecycle are usually called an aircraft programme, as shown in Fig. 2.3 (Roskam, 1985). It is based on these phases that a first preliminary cost estimation can be performed. There are some differences between stages of product lifecycle and aircraft programme, with each author using its own taxonomy. Figure 2.3 shows the phases of an aircraft programme used for cost estimation purposes, in which the first three phases of a generic lifecycle are grouped into a single phase of Research, Development, Testing and Evaluation (RDTE). The same Figure depicts the transition phases of ramp-up (to be discussed ahead) and sale (that signals the point in time of transfer of ownership).

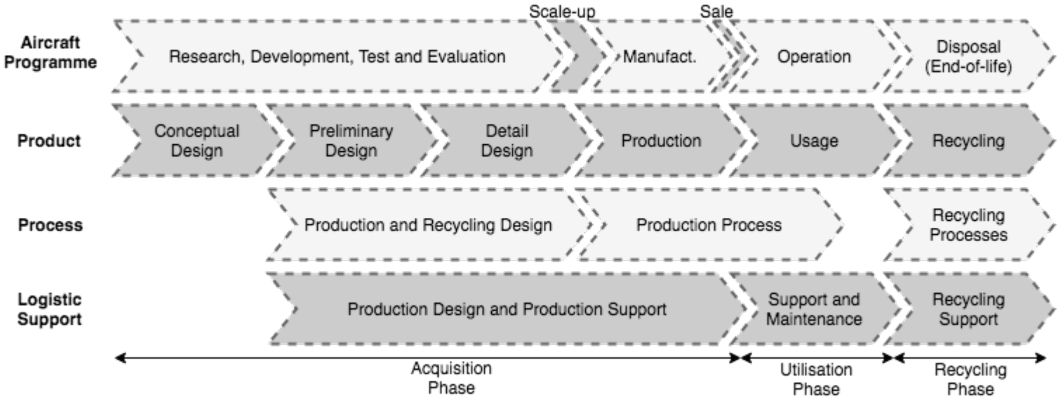

Figure 2.3: Phases of aircraft programme and system lifecycle. Adapted from Roskam (1985) and Kriwet et al. (1995).

2.4 | Summary of Chapter 2

This chapter introduced the reader to the aerospace industry. It was shown that an aircraft lifecycle can be as long as 30 years or more, and that aircraft are extremely complex products that can be composed of up to 4 million different parts. OEMs are confident that air travel market is expanding and there are opportunities for launching new programmes. Especially with the increase of fuel price, demand for lighter aircraft is also a driver for market expansion. There are few OEMs - acting mainly as systems' integrators - but there are many suppliers grouped in different tiers, and even some are considered strategic partners. Another critical observation to retain is that this industry is global and materials/systems are sourced from many different locations. Such long and complex SCs are very sensitive, vulnerable and prone to disruptions, requiring additional efforts to coordinate across all tiers. Events in the Boeing 787 programme have been introduced as a showcase of what can go wrong when risk-sharing strategies fail. Even so, risk-sharing strategies and strategic alliances continue to prevail and are the way to go in cases of great system complexity like this industry.

The next chapter is dedicated to study aspects related with sustainability and lifecycle management but also more technical topics such as advanced materials and their respective manufacturing processes, cost estimation techniques, and SCM.

3 | Literature Review

Having presented the Aerospace Industry and context for the problem, now the most relevant topics for the problem are reviewed. By the end of the chapter, the reader is expected to hold key ideas of new advanced materials, cost estimation and SCM.

This chapter is divided into three sections, according to the theoretical foundations required for the model. First section focuses on Advanced Materials for Mobility Industries, presenting a historical perspective of the evolution of materials and the most appropriate manufacturing processes. Then follows a complete review of Cost Estimation Techniques, discussing common models for cost estimation in general and specific models for the aerospace industry. Section three is reserved for a comprehensive review of Supply Chain Management aspects, discussing sustainability, optimisation methods and the influences of NPD in SCs. The last section summarises the essential topics reviewed along the chapter so that critical ideas can be passed to the next stages of the research.

3.1 | Advanced Materials for Mobility Industries

This section focuses on polymer-based advanced composites and includes an overview of the context and advantages of these materials. A review of main manufacturing processes is presented, along with a set of real industrial applications of these materials.

The history of materials used in mobility industries is marked by improvements and innovations towards lightness, versatility and flexibility. Resetar et al. (1991) divides the advanced materials into two main groups: advanced composite materials and metal alloys. Ceramic-matrix composites, polymer-matrix composites and metal-matrix composites fall in the category of advanced composite materials, while aluminium-lithium and powder metallurgy alloys logically fall in the metal alloys. Advanced composites are combined at a macroscopic level resulting in a heterogeneous material, whereas the alloys are combined at a microscopic level; the result is a different homogeneous material with properties distinct from its constituent elements (Zaloom and Miller, 1982). The main advantage of the composite materials is a reduction in weight, which can be made up to 80% lighter than their equivalent steel parts, or 20% to 50% if replacing similar aluminium parts (Jones and Bert, 1999; Zaloom and Miller, 1982; Mazumdar, 2002). From Fig. 3.1 it can be noticed the move towards these advanced materials, as Ashby et al. (1987) anticipated. The use of composite materials showed steady growth over the years, even though the pace of adoption might not have been as fast as predicted by Ashby et al. (1987) and others, especially in the aerospace industry. Despite the obvious advantages of fibre-reinforced composites, the prohibiting costs of development, manufacturing and certification explain the 'slower-than-anticipated' rate of adoption. Temperature limitations compared to other alloys, poor performance against mechanical damage and poor 'through-thickness strength' were also slowdown factors (Baker et al., 2004). Composite materials result from the combination of more than one element whose joint properties offset the limitations of each component (Zaloom and Miller, 1982; Brigante, 2014). The matrix holds thousands or millions of filaments together, as these can be woven together or arranged in many different ways to form textile plies (or layers). The matrix distributes the load evenly along the fibres and is responsible for other characteristics such as "service temperature, resistance to chemicals

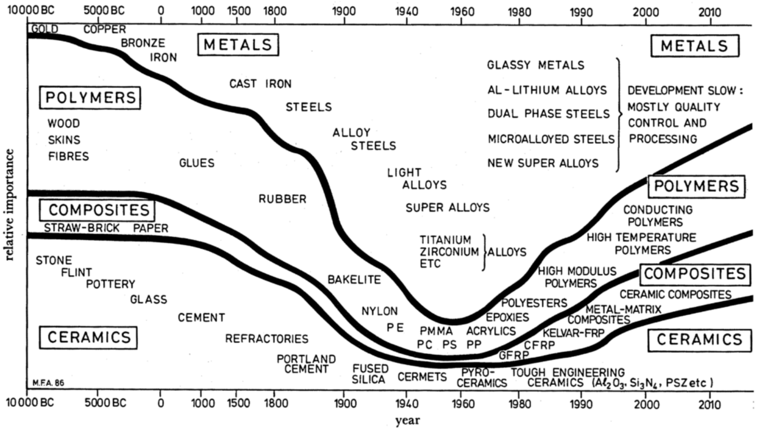

Figure 3.1: Evolution of engineered materials. Source: Ashby et al. (1987).

[and] damage tolerance" (Gay et al., 2003; Resetar et al., 1991). Complex products benefit from the use of composites as it potentially reduces the part count when compared with ordinary materials. Hence, reliability can be improved while achieving weight and cost reduction for such structures (Ageorges and Ye, 2002). Defining standards for these materials poses difficulties due to the wide range of possible element combinations and lack of sufficient material knowledge. Subjects studied in fracture mechanics (i.e., shear and compressive loads) have no linear pattern for all composite materials, which may result in hidden delamination and poor performance of the final structure (Resetar et al., 1991).

For this research, the focus will be on carbon fibre polymer-matrix composites (hereafter referred to only as composites interchangeably) as their properties make them most suitable for mobility industries, especially aerospace (Resetar et al., 1991; IAMAT, 2017). These are described in the next section.

3.1.1 | Polymer-Matrix Composites

The attractiveness of polymers for various commercial applications derives from the low density of these materials (Ma, 2011). The more relevant aspects of these composites such as fibres, matrices, manufacturing processes, and the details of each element are reviewed below.

Fibres are the reinforcing element of composite systems, commonly known as fabric. Fabrics for a wide range of applications are named after their constituent material (e.g., glass, carbon, aramid/kevlar and boron). Typical classifications are made using the length of the fibre, ranging from single particles to long and continuous fibres. Particle and fibre reinforcements are more frequently used, the former being much cheaper than the latter but also presenting relatively lower performance (Ma, 2011). Another reason for the use of reinforcing elements is their cost compared to that of the matrix constituent; hence, cost, ease of processing and mechanical properties (such as stiffness, strength or fracture behaviour) are all aspects to consider for the choice of a reinforcing element (Mitschang and Hildebrandt, 2012). Low-to-medium precision and performance applications of composites can use short fibres or particles as reinforcement, bequeathing the matrix to bear most of the load (Brigante, 2014). Here the primary concern is to achieve an even distribution of the material for homogeneous finishing (Advani and Hsiao, 2012). Contrarily, high-performing materials use long and continuous fibres (either aligned lengthwise, forming layers or woven together according to design) that act as primary load-support (Brigante, 2014).

For these long-fibre systems, filling with resin between fibre void regions is the issue of concern for manufacturers; otherwise, delamination or debonding may occur when loads are applied. Complex shapes are more difficult to produce from long fibres implying a trade-off between performance and complexity (Ageorges and Ye, 2002; van Hattum et al., 2011). The orientation of the fibres (uni- or multi-directional) also influences the stiffness and strength of the materials (Advani and Hsiao, 2012).

The matrix is the linking element, providing stability and protection to the reinforcing material. Polymeric matrices can be either made out of thermosetting or thermoplastic resins (elastomers are not considered for this research) (Mitschang and Hildebrandt, 2012; Brigante, 2014). Starting with thermoset resins, when subject to a designated temperature and/or pressure (cure cycle), these undergo a chemical reaction called cross-link bonding (Resetar et al., 1991). This reaction alters the material, thus making thermosetting resin to be known for its irreversibility due to the impossibility to return it to a liquid state after the polymerisation process (Brigante, 2014). Despite the slow curing process (e.g., 8-12 hours for epoxy), thermosetting resins are better known than thermoplastics. Some advantages include low curing temperatures (around 180° C for epoxies) and resistance to high temperatures and solvents (Resetar et al., 1991). Typical thermosetting resins are polyester, epoxy and polyurethane (Mitschang and Hildebrandt, 2012).

Thermoplastic resins, on the other hand, have higher viscosity and turn into a liquid state as the temperature increases, solidifying with cooler temperatures (Brigante, 2014). Thermoplastics potentially reduce manufacturing costs due to shorter processing times and the possibility of reheating and reforming the parts. Conversely, the cost of raw materials and operating temperatures are higher. On top of that, there is still poor knowledge regarding the behaviour of these materials (Resetar et al., 1991). With higher processing temperatures, storage and transportation do not require refrigeration (low risk of unintended polymerisation), resulting in increased shelf-life (Resetar et al., 1991). Common thermoplastics used in industries are polypropylene (PP), polyethylene (PE), polyamide (PA), acrylonitrile-butadiene-styrene (ABS), polyurethane (PUR), polyvinylchloride (PVC) (Mitschang and Hildebrandt, 2012).

Composite parts manufacturers can use either dry sheets (later to be locally impregnated with resin) or pre-impregnated fabrics ('*prepregs*'). The first process, known as wet lay-up, may entail lower costs but the quality of resulting parts is highly dependent on 'employee's craftsmanship' (van Hattum et al., 2011). For the second process, sheets or plies of dry carbon fabric (with unidirectional or woven fibres) are pre-impregnated as a way to simplify the lay-up process and to ensure that the 'fibre-to-resin ratio' is under control (Haresceugh et al., 1994). This type of material is more expensive than *in situ* resin infusion of dry plies; but results in lower manufacturing time, as it consists only of stacking, compacting and consolidating plies into a laminate. The *prepregs* are semi-cured and its final consolidation requires heat; thus, cooled storage and transportation are often a requirement (Mårtensson et al., 2015; González et al., 2017).

Carbon fibres are produced from organic fibres (e.g., rayon or polyacrylonitrile (PAN)) through a process called graphitisation involving submission to an inert atmosphere at around 2000° C. Hence, Carbon Fibre-Reinforced Polymers (CFRPs) have been used for high-performance applications due to the exceptional mechanical properties of high Young's modulus and low density, which result from the crystal structure of graphite. The high cost of carbon fibres is owed to the energy-intensive manufacturing process (Brigante, 2014).

3.1.2 | Composites Manufacturing Process

The use of new advanced materials for typical commercial applications is only viable if there is an efficient method for manufacturing; hence, the selection of the right process is a critical aspect of NPD. This selection may be subject to different criteria: (1) production rate/speed need, (2) cost constraints, (3) performance requirements, (4) size and (5) shape of parts (Mazumdar, 2002).

CFRPs are one-dimensional reinforcements (a characteristic of anisotropic materials) that must be formed to give fibres the desired orientation resulting in two- or three-dimensional parts with the desired shapes and strengths. This process is called forming and is an integral part of composite components manufacturing process, allowing for the resulting piece to be a solid and consistent product (Baker et al., 2004). The following generic steps are constituent of the forming processes for composite structures (Mazumdar, 2002; Gay et al., 2003): **impregnation**, **lay-up**, **consolidation** and **solidification**. These steps are present in all manufacturing processes, although their actual order may vary.

- **Impregnation/wetting** - Combination of fibres and resins resulting in a lamina (very thin layer). The fabric layers are bathed in the matrix material, according to desired thickness and properties. The goal is to ensure the fibres are integrated with the resin and that the resin flows along all fibres. Viscosity, surface tension and capillary motion can influence the process. Thermoplastics may require pressure to achieve even distribution due to their higher viscosity.
- **Lay-up** - It is the step in which laminates are made. Several layers of impregnated fabric or *prepregs* are laid-up on tools according to the desired format and thickness of the final piece.
- **Consolidation** - During the consolidation process, the air in-between layers and every void are eliminated from the part. This is achieved by applying pressure and ensuring the resin flows evenly through the total extent of the piece (compaction).
- **Solidification/cure** - Solidification consists in applying a cure cycle to achieve polymerisation of the matrix.

Baker et al. (2004) details the complete manufacturing process as follows: (1) source and prepare material, (2) cutting/kitting, (3) automated or hand lay-up, (4) bagging, (5) curing, (6) debagging, (7) finishing and painting, and (8) trimming. Additional activities can be considered such as previous tool preparation, assembly of cured components, and Non-Destructive Testing (NDT) (to ensure the parts are damage-free) (Baker et al., 2004). For processes based on resin infusion, lay-up will occur before resin embeddedness. Composite parts are obtained only after the final stage of the process (solidification or cure), during which the polymer is hardened. This process is an important cost driver of composites (Gay et al., 2003).

As this research is an integral part of the project IAMAT (2017), the focus is only on four forming processes - the evaluating processes for the optimisation model -, aiming to identify the efficient alternative (IAMAT, 2017): (1) **TA process**, (2) **VARI**, (3) **VBO** and (4) **TS**. These processes are described next, illustrations for each can be found in annexed figures A.1, A.2, A.3 and A.4.

Brigante (2014) classifies available technologies based on their properties of closed- or open-mould, continuous or discontinuous, and manual or automated processes. However, if based on the type of cure, the techniques can be classified as Autoclave-cured or Out-of-Autoclave (OoA) (Centea et al., 2014).

The TA process is the current standard for high-performance applications. The process starts with the lay-up of *prepreg* plies onto the prepared tool; these are stacked according to the design model. If required, other components are added such as stiffeners, adhesives, dry fabric or honeycomb core, and cloths (which allow for the excess resin to flow). As soon as the kit is prepared and assembled, a vacuum bag is applied and everything is placed in the autoclave. Inside the autoclave, temperature activates polymerisation of the matrix and pressure eliminates the voids from the part, according to a cure cycle (Advani and Hsiao, 2012). This process is onerous, owing to the energy consumption of pressure vessels, nitrogen fillings and long cure cycles (González et al., 2017). Besides, the size of the vessels and production rates are limiting factors for the parts that can be produced (Centea et al., 2014). In addition to the aforementioned disadvantages of cost, lack of flexibility and inefficiency, autoclaving also requires long processing times and substantial upfront investments (Advani and Hsiao, 2012).

OoA-based manufacturing processes have been developed to overcome such disadvantages, and its use has been increasing. Although the majority of OoA processes is based on liquid moulding (dry fabrics locally embedded with resin), the development of OoA *prepregs* is now enabling more applications. VARI is an example of these OoA techniques - a variant of Resin-Transfer Moulding (RTM) where an open-mould is used, and low pressure is required for the cure. On the other hand, VBO is based on *prepreg* plies (Centea et al., 2014; González et al., 2017).

Like other liquid moulding processes, VARI consists of covering the dry fabric over the open-mould with a flexible vacuum bag and allowing the resin to flow into the vacuum bag. The flow of thermosetting resin into the bag is due to atmospheric pressure, which explains the long times of fluid infiltration and may result in uneven coverage or presence of voids (González et al., 2017). This is followed by curing (up to 200° C, using a conventional oven), demoulding and finishing of the parts. This technique requires additional finishing steps since there is no mould for one of the sides of the part. The process is attractive due to low-cost tooling and scalability of large components (Goren and Atas, 2008).

Another alternative is using VBO for the forming process, made possible thanks to OoA thermosetting *prepregs*. The process is similar to autoclaving: the lay-up of OoA *prepreg* plies over the cleaned tools, followed by coverage with a vacuum bag. After the laminate is formed and the bag is assembled and sealed, the kit is subject to a cure cycle. The curing process starts with a low-temperature and vacuum environment to release entrapped air, followed by one or more high-temperature cycles for the actual curing (Centea and Nutt, 2015). The advantage of this technique is the possibility to produce parts with a quality level comparable to those autoclave-processed, without the downsides of actually using TA. The curing process for VBO is possible by resorting only to conventional ovens or heating blankets, and no particular high-pressure environment is required (Centea et al., 2014). This process entails lower investment, is easy to use and enables the simultaneous cure of a large number of parts. However, process and debulking times are longer and energy consumption is higher. On top of that, curing is space-limited, special bagging is needed (subject to material cost and availability), and the use of new materials requires additional qualifications (Advani and Hsiao, 2012). Again, the problem with low-pressure methods is the potential increase in void-formation due to entrapped air between plies, which may result in a prolonged period for extraction of air (Centea et al., 2014).

The last process is based on thermoplastic matrix composites. The higher viscosity of the material increases the cost for impregnation of continuous fibres, due to increased difficulty in melting the polymer or the need to use solvents. Conversely, thermoplastic *prepregs* can be used, for which compression-based forming is the most used process (Månson et al., 1999; Silva et al., 2011). TS is a technique adapted from the known sheet metal stamping, by using a heated press, and the same principles can be applied to thermoplastic composites sheets (preferably, with short-fibre reinforcement). For typical metal stamping/pressing, the process consists in placing a flat sheet metal into a stamping press where a tool and a die form the metal into the desired shape (Resetar et al., 1991).

3.1.2.1 | Composites Waste Flows and Recycling

Although there are no official figures, Snudden et al. (2014) advances that 853 is the amount of carbon fibre *prepreg* scrap, in tonnes, produced by automotive industry alone in 1997, and rough estimates indicate that composites manufacturing waste vary between 10% and 30%. Advanced composites waste can result from: (1) uncured or dry material/liquid resin rolls and scrap, (2) uncured trim, (3) cured trim, (4) cured scrap and (5) end of life (Snudden et al., 2014).

Snudden et al. (2014) mentions a study in the US of users of advanced composites where, among these, the majority of scrap generated is the result from uncured *prepreg* (66%). Moreover, around 68.5% of the waste generated could be saved or avoided, being hand lay-up the leading cause of waste; typical manual procedures only use roughly 40% of the available material. It is known that the preparation of plies from the feedstock rolls generate scrap from 25% to 50% of the input material. The amount of scrap produced is a function of the geometric complexity of parts; thus, the reduction of part complexity may result in a decrease of scrap (Mårtensson et al., 2015).

Landfill and incineration have long been the options for dealing with composite waste (Rybicka et al., 2015). Greener alternatives for waste disposal of composites are subject to several factors that drive recycling suitability for companies: technical, logistic, financial, confidence, supply and demand, and legislative (Goodship, 2010). Up until now, resorting to landfill was the financially viable option for manufacturers, and the lack of attractiveness of reused and recycled products (both from the economic point of view and the perceived quality) were limiting aspects of adequate waste disposal (Snudden et al., 2014). The perceived lower performance of recycled carbon fibre against virgin fibres combined with the lack of control over properties (such as fibre length or surface quality), explains the resistance to further use by industries (Oliveux et al., 2015). Thermosetting resins (that cannot be melted) or the presence of fillers and fibres increase difficulties for the recycling process (Baillie, 2004). Fortunately, the European Union (EU) has been enforcing reduction of the environmental impact of these materials by setting penalties and incentives for industries, promoting the dissociation of waste production from economic growth. Acting on the prevention side, setting emission limits and expanding markets for reused, recycled and recovered products are examples of strategies in the EU environmental plan (Goodship, 2010).

Mechanical grinding, thermal processing, solvolysis, pyrolysis, thermo-mechanical recovery or fluidised bed are among the portfolio of alternatives to incineration and landfill for waste disposal (Pickering, 2004; Rybicka et al., 2015; Snudden et al., 2014). Even so, each type of fibre-reinforced polymer may require specific treatment. All fibre composites can be subject to granulation/pulverisation and be used later as fillers. Short-fibre thermoplastics can either undergo granulation and remoulding or dissolution/separation, for fibres and polymers to be reused. Whereas long-fibre thermoplastics, either go through dissolution/separation or thermal processing, resulting in the reuse of both fibres and the polymer. Given the appropriate treatment, some fibres can be reused for fuel/energy (Baillie, 2004). The mechanical process requires a continuous flow of raw material for a dedicated operating facility to be viable (Snudden et al., 2014). Solvolysis and pyrolysis processes allow to retrieve high-quality carbon fibres; yet, these are temperature- and energy-intensive processes (Das, 2010; Oliveux et al., 2015). The feasibility of most of these processes depends on the economic gains associated. In the case of carbon fibres, given the high cost of production of virgin fibres, the value of resulting fibres may offset the costly recycling process (Baillie, 2004).

3.2 | Cost Estimation Techniques

This section introduces the main concepts of cost estimation to be used in the following stages of research. References are made to the importance of cost estimation, moving on to the presentation of general techniques and closing with particular cases of estimation applied to aerospace.

First, and according to the Society of Cost Estimating and Analysis (2017), cost may have different interpretations: (1) monetary value of an item, (2) amount paid/to be paid for a purchase, and (3) loss or penalty. Cost estimation can be defined as the ’art’ and ’technology’ of computing the probable (monetary) value. This value is based on historical information available and "quantitative models, techniques, tools, and databases in order to predict an estimate of the future cost of an item, product, program or task" (ICEAA, n.d.; Mislick and Nussbaum, 2015).

There are different types of costs to be considered during the process of cost estimation: recurring, non-recurring, direct, indirect, fixed, variable, overhead and sunk costs (Mislick and Nussbaum, 2015). Even though, the same general techniques for estimation - to be discussed next - can be used.

3.2.1 | General Techniques

The literature on cost estimation overlay several topics, ranging from manufacturing products to services either on early or advanced stages of development. Regarding the traditional cost estimating, there are two relevant points in time for assessment of estimates: a first rough estimate at the early stage of development, and, later, a more detailed, thorough estimate at the end of development (Rush and Roy, 2000; Curran et al., 2004).

For Boehm et al. (1981), the costing techniques fall into seven different categories: (1) algorithmic/parametric, as function of design variables; (2) expert judgement, through knowledge of professionals; (3) analogy, by comparison with completed projects; (4) Parkinson, that adjusts estimates to available resources; (5) price-to-win, which produces the estimate to win the contract; (6) top-down, whose total estimate derives from a holistic view of product; and (7) bottom-up, where total cost estimation derives from the aggregation of the individual parts. For Curran et al. (2004), there are only three types: (1) bottom-up, (2) analogous, and (3) parametric method. Later, Niazi et al. (2006) recommended a division into qualitative (i.e., intuitive and analogical techniques) and quantitative methods (i.e., parametric and analytical tools).

Qualitative techniques are based on historical information and data from previous similar products, enabling a preliminary estimate in the conceptual phase; whereas quantitative methods are a function of an analytical expression that includes product's characteristics, processes, features and design, acting as parameters that can be multiplied or added. On the other hand, quantitative methods are used in more advanced phases of development due to the requirement of detailed knowledge about product and processes (Niazi et al., 2006). Since cost modelling is 'knowledge-intensive', more knowledge about the product and the costs is available during the final stages of production, leading to more accurate estimates (Boehm et al., 1981; Curran et al., 2004)

Starting with the intuitive techniques, belonging to the qualitative group, these can be further split in case-based and decision-support. The case-based approach estimates cost for a new design from an earlier or similar version of a product in the database, with the necessary adjustments or modifications, resorting to an information system for storing all previous design cases. Using decision support systems is another approach for cost estimation that draws on the know-how and expertise from specialists to build knowledge-based models. Decision support methods include (1) rule-based systems, where constraints in manufacturing processes are modelled as rules; (2) fuzzy logic, that allows dealing with imprecision and uncertainty by establishing fuzzy rules; and (3) expert systems, relying on a knowledge database and a model that generates estimates.

Analogical techniques also rely on past data to estimate costs for new designs, using regression or neural network models. Regression models are similar to the usual linear regression, where an existing relationship between variables enables extrapolation for new observations. The neural network is a non-parametric approximation model trained from previous knowledge, allowing prediction of costs of new designs by fitting curves to data without a specific function which. Contrary to regression, it tolerates non-linear relations (Niazi et al., 2006; Duran et al., 2009).

Quantitative methods fall into two categories: parametric methods and analytical techniques. Parametric methods have a straightforward definition: the use of a structured process of estimating the components/parameters through statistical methodologies. The total cost is derived from each cost driver and the relations may not be linear.

Analytical techniques decompose each product into unitary elements such as materials and processes. There are five approaches: (1) operation-based, (2) break-down, (3) tolerance-based, (4) feature-based, and (5) Activity-Based Costing (ABC). The operation-based approach estimates the amount of time of each manufacturing, non-productive and set-up operation, which translates into a cost structure. The break-down approach method consists of summing all costs incurred in a cycle (material, labour, machining, tooling, set-up, overhead, etc.) to derive the total cost estimate for the product. The tolerance-based model is composed of alternative designs and tolerance regions, allowing changes in the design without affecting the estimates in large scale, still minimising the cost function. Another model of the quantitative type is the feature-based cost estimation, which is based on the selecting among cost-driving features of a product (such as particular materials, specific designs or manufacturing processes). Last, the ABC system which is based on computing costs after the manufacturing and parallel activities required for a product to be developed and produced. This method assigns general expenses and other indirect costs (e.g., overheads) to each unit. By establishing a relation between activities, costs and products, designers are able to estimate the impact of design alternatives on the total cost (Niazi et al., 2006).

The workflow for cost estimation process may differ depending on the chosen technique. For parametric methods, the central principle is to develop the Cost Estimation Relationships (CERs) and, from that, to derive the associated curve for parametrisation (Agyapong-Kodua et al., 2011). These CERs represent simple ratios or complex equations of multiple independent variables. If cost is proportional and a linear relationship with a single variable exists, it is known as cost factor or driver (expressed as a ratio or percentage) and can be used as a multiplier.

Analogy techniques are dependent on the information of these cost factors, retrieved from historical data, and should be applied when data is scarce (Mislick and Nussbaum, 2015). After having characterised all the requirements of the project or product, the first stage is to identify data sources and, then, proceed with data collection (quantitatively and qualitatively) from historical databases and experts. As mentioned before, cost factors are derived from this information and are used to generate the actual cost estimates (Agyapong-Kodua et al., 2011). Besides, the task of combining different data sources with multiple time periods may require data normalisation for the comparison of different periods to be possible and meaningful (Mislick and Nussbaum, 2015). According to NASA (2015), a typical project cost estimation process includes several steps: (1) Project Definition Tasks, namely understand requirements and build a Work Breakdown Structure (WBS), (2) Cost Methodology Tasks, such as definition of ground rules and selection of cost estimation methodology, and (3) Cost Estimate Tasks, i.e., developing the actual cost estimation, include an associated risk assessment, and document and present the cost estimates.

In 2011, Agyapong-Kodua et al. presented a new classification for cost estimation techniques, maintaining the separation between qualitative and quantitative techniques. The parametric, the fuzzy logic and the neural network methods are now grouped as statistical methods, within the quantitative group that also included analogous, feature-based and generative-analytical techniques. The strong point of statistical models found in research is the ability to identify correlations between variables/features and cost of the product, allowing the construction of parametric models (Son, 1991; Curran et al., 2004; Agyapong-Kodua et al., 2014). For the qualitative methods, there were only two types: expert judgement and heuristics. This new framework is illustrated in Fig. 3.2. Hart et al. (2012) developed an advanced statistical model that makes use of principal component analysis as variable selection technique, which allows the identification of cost-impacting factors and serves as input for a cost-predicting regression model. The baseline for cost estimation tools remained essentially unchanged from 2000 onwards; essentially differing on more capable computer powerhouse required to perform calculations and simulations. Monte Carlo simulation is an important asset to derive probability distributions that fit the historical data and allow for the estimation of the cost of new designs (Agyapong-Kodua et al., 2011; Mislick and Nussbaum, 2015). As referred in the previous chapter, the product design phase has the

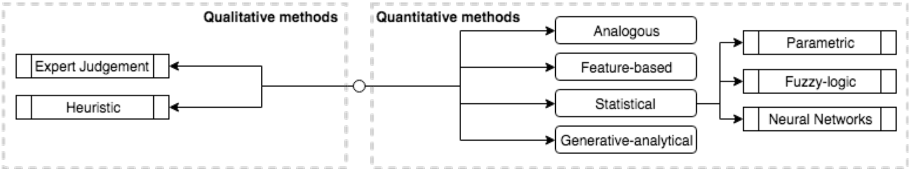

Figure 3.2: Cost estimation methods. Adapted from Agyapong-Kodua et al. (2011).

highest potential for cost reduction regarding the whole lifecycle, as it is possible to see in the Fig. 3.3. Techniques of concurrent engineering and design for 'something' (DFX) have been adopted, with particular focus on the design for cost (DFC) (Asiedu and Gu, 1998). The wide variety of models for cost estimation available in literature focuses on later stages of NPD process rather than at the beginning of it. These models present shortcomings in capabilities that are essential at that stage, e.g., material selection, among other functionalities. This gap originated the development of integrated computer- and knowledge-based systems for cost modelling, combined with Computer Aided Design/Manufacturing (CAD/CAM) systems, capable of identifying the most economical materials and manufacturing processes (Shehab and Abdalla, 2001, 2002). The use of CAD/CAM tools with a feature-based costing approach enabled a design for cost strategy, where design is conditioned according to the highest cost factors (Ou-Yang and Lin, 1997). Based on similar principles, Jha et al. (2007) tested a model for cost optimisation that combined four different software tools: (1) SolidWorks, for design, (2) ANSYS, for finite element analysis, (3) SEER-DFM, for cost estimation, and (4) GA-Lib, for optimisation using genetic algorithm. This integration enabled the optimisation in the design phase while attending to constraints from tools of other functional areas involved in product design.

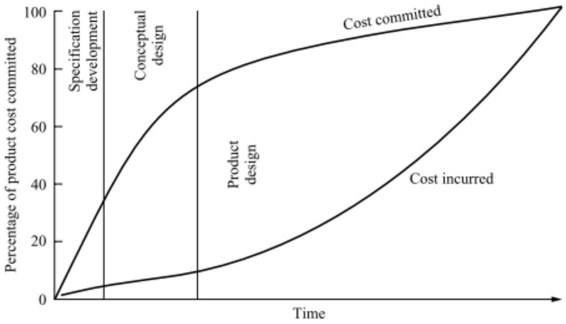

Figure 3.3: Evolution of costs across the design period. Source: Ullman (2010).

If any historical data is to be used for future cost estimation, there is the risk that this information is related to expenses incurred or estimates performed in different periods of time; thus requiring normalisation. Multiple techniques can be used to compare different investment alternatives, and a common method for this is using the Net Present Value (NPV) as a measure of economic performance of each option. NPV represents a discount (or interest) rate that is multiplied to reduce revenues or expenses to a single discounted net value. It allows for the comparison of benefits and costs occurred in different years that otherwise would not make sense (NASA, 2015; Mislick and Nussbaum, 2015).

Hueber et al. (2016) uses the aforementioned classification presented by Curran et al. (2004) to develop estimation models dedicated to the aerospace industry. These particular models will be discussed over the next section.

3.2.2 | Cost Estimation in Aerospace

Here are presented the aspects of cost estimation related to the aerospace environment. OEMs are responsible for marketing the aircraft, and a major impact factor on the success of sales is price (Asiedu and Gu, 1998). Thus, the mission of OEMs is to ensure cost-efficiency along product lifecycle stages and, as a consequence, to promote the same across the SC. In the next paragraphs, the issues of cost estimation for manufacturing activities and LCC are discussed.

As introduced earlier, the lifecycle of a product is the time span from ’birth’ to ’death’ of that product, including all the stages that it goes through in-between. Furthermore, LCC yields an estimate for the number of resources that are necessary throughout that time interval, starting with the R&D phase, followed by production/manufacturing, the operating and support, and disposal stages (Mislick and Nussbaum, 2015). The operating and support stage is more of a responsibility of airlines rather than OEMs, so this stage will not be discussed. The total cost of the lifecycle is derived from the sum of all costs from intermediary stages (Roskam, 1985). A total cost breakdown was suggested by Fabrycky and Blanchard (1991) and Asiedu and Gu (1998). Based on that, Xu et al. (2006) also described the cost elements that constitute each stage of LCC, which are presented below:

- **Design stage:** Engineering design cost, Drawing cost, Computer processing cost, Design modification cost, Production preparation cost, Management cost;
- **Manufacturing stage:** Material cost, Facility cost, Production cost;
- **Marketing and after-sale stage:** Marketing cost, Distribution cost, Maintenance cost;
- **Disposal and recycling stage:** Retrieval cost, Disassembly cost, Reprocessing cost, Landfill cost.

Following this approach of LCC, comes the R&D phase which includes all costs related to research and development activities, either for new or updated parts or products. This stage is also called RDTE (Mislick and Nussbaum, 2015). Roskam (1985) includes seven cost sources for this cost heading: (1) Airframe Engineering and Design Cost, (2) Development Support and Testing Cost, (3) Flight Test Airplanes Cost, (4) Flight Test Operations Cost, (5) Test and Simulation Facilities, (6) RDTE Profit, and (7) Cost to finance the RDTE. Additionally, the costs of developing, manufacturing and flight testing prototypes should also be included in the RDTE phase. All these components can be estimated through the generic cost estimation techniques presented earlier. Roskam (1985) details how to estimate these costs using a parametric approach based on weight and size that can be applied to other commercial and military aircraft designs.

Then comes the production or manufacturing stage of the product lifecycle. This is the investment phase, in which primary and support equipment is acquired, training is required, and also performance, scale and process studies are made (Mislick and Nussbaum, 2015). Roskam (1985) breaks this stage into fours cost components: (1) Airframe Engineering and Design Cost, (2) Airplane Production Cost, (3) Production Flight Test Operations Cost, and (4) Cost of financing the manufacturing programme. In aerospace, new products usually derive from the improvement of previous successful designs. Hence, analogous costing techniques have been widely used (Curran et al., 2005).

For the particular case of composites composite manufacturing cost estimation, a model from the

Advanced Composites Cost Estimating Manual (ACCEM) was one of the pioneers for this purpose. It consisted of parametric equations, a database with prices of materials, labour standards and learning curves (Zaloom and Miller, 1982). There are other models for composite manufacturing cost estimation such as the Cost Optimisation Software for Transport Aircraft Design Evaluation (COSTADE), or in which several information sources are combined. For instance, COSTADE with CAD and/or Finite Element (FE) model, or integrated into other tools (e.g., Ansys Parametric Design Language (APDL)) (Barlow et al., 2002; Hueber et al., 2016). Here, the goal of COSTADE is to enable cost reduction of advanced composite structures (Freeman, 1992; Mabson et al., 1996).

Last, the disposal stage, composed of a set of processes for dealing with a system after its useful life has ended. Examples of these activities/processes may be demilitarisation, detoxification/neutralisation, waste storage and environmental restoration (Mislick and Nussbaum, 2015). End-of-life is reached if benefits from structural repairs no longer offset the costs of those repairs, an aircraft is outperformed by modern versions, the technology is obsolete, or the damage is beyond repair. The disposal consists of temporary storage, depletion and disposal of internal fluids, disassembly of all parts and systems, tearing apart the airframe and disposal of all components. There are costs associated with all these activities that can be estimated through analogous methods, even though there may be salvage value for some of the components being dismantled (Roskam, 1985).

3.3 | Supply Chain Management

The historical evolution of aerospace SC and its distinctive characteristics were presented in the previous chapter as part of the introduction to the problem. The key aspects of aerospace SC to retain are (1) the fact that OEMs partner with few strategic partners, (2) that OEMs act as integrators and rely on suppliers for most of the manufacturing functions in collaborative relations, (3) that those suppliers are spread across the globe due to strategic sourcing and (4) that the SCs are very long and complex.

Recalling the goal of this research to develop a model for optimisation of the aerospace SC as a whole, this means the optimisation across all product's lifecycle stages. Increasing concerns about sustainable, social-responsible and environmental-friendly practices along SCs make it imperious to discuss Sustainable Supply Chain Management (SSCM) topics (Carter and Rogers, 2008; Gopalakrishnan et al., 2012; Barbosa-Póvoa et al., 2018).

Hence, the purpose of this section is to explore the more relevant aspects of SCM theory that are spanned across the literature. Accordingly, the section is divided into three main topics. A first topic to discuss sustainability and environment-related issues in the SC and a second one regarding optimisation methods. The third and last topic discusses the aspects of NPD and production scale-up in the SC - also issues within the scope of SCM (Chopra and Meindl, 2013).

3.3.1 | Sustainable Supply Chain Management

Environmental impacts and issues resulting from economic activities can no longer be overlooked. Fast depletion of resources leading to scarcity, growing world population, hazard emissions, climate changes and global warming are all root causes of unsustainable global development (Mota et al., 2015; Gopalakrishnan et al., 2012). The World Commission on Environment and Development (WCED), under

Brundtland's presidency in 1987, defined sustainable development as the one "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Carter and Rogers, 2008). Although not exclusively, climate change and global warming are being caused by global sourcing strategies, operations, transportation, poor waste management, pollution, exhausting resource depletion and dangerous carbon emissions (Gopalakrishnan et al., 2012).

That being said, Ahi and Searcy (2013) defined SSCM as the coordinated and voluntary inter-organisational effort of integrating economic, social and environmental concerns into every aspect of typical SCM to "meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term". The main factors that have been driving sustainable development in companies are (1) government legislation, (2) stakeholder pressures, (3) resource depletion, (4) low carbon economy, (5) environmental standards and (6) social responsibility. These reasons have been pushing companies to focus not only on pursuing profit and shareholder's satisfaction but also to minimise environmental and social impacts of their activities and policies (Gopalakrishnan et al., 2012).

As mentioned above, the trend is set and more companies grow interests in implementing green strategies and pursue sustainable development. European Commission (2013) states its vision for environmental policies as follows: "In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society". An evidence of this trend is the study with 300 companies reporting that 50% of the companies had planned SC redesign towards sustainability, and around 80% were in need to guarantee compliance with green policies (Chaabane et al., 2017).

Following the same trend, this dissertation focuses on using the Triple Bottom Line (3BL) performance measures of SCs. This term, coined by Elkington (2004), consists of adding the environmental and social dimensions to the traditional economic performance indicator. Both academics and companies have been adopting the 3BL as businesses' performance measures (Elkington, 2004; Carter and Rogers, 2008). It is believed that these measures force companies' structures and partners' alignment towards long-term sustainability and resilience (Elkington, 2004; Gopalakrishnan et al., 2012).

Environmental-friendly practices by companies may lead to higher financial performances and improved competitive positions. This is due to productivity and efficiency gains as well as the increased reputation resulting in sales, among other potential economic gains (Gopalakrishnan et al., 2012; Carter and Rogers, 2008). However, the three dimensions have not been deemed of equal importance, with the social component still being relegated to a background position (Seuring, 2013). Mota, Gomes and Barbosa-Póvoa (2014) and Barbosa-Póvoa et al. (2018) draw the same conclusion, that the social dimension has not been given much attention by literature; moreover, it is extremely difficult to define and to find suitable metrics. In the SC optimisation model developed by Mota, Gomes and Barbosa-Póvoa (2014), these social aspects were captured through GDP per capita and the unemployment rate, which can be considered indirect measures of social impact.

A pivotal aspect of using 3BL as companies' performance measures is related to computing the values for each dimension. Section 3.2 showed how to estimate the economic aspects of SC: here the focus is on estimating the environmental parameters. LCA dominates the measurement tools for the environmental dimension of the 3BL and is classified as a reliable method for quantification of polluting emissions, resource and energy consumption, and environmental and health repercussions of products and/or processes lifecycles (Seuring, 2013; Mota, Gomes, Carvalho and Barbosa-Póvoa, 2014). The typical LCA process is composed of 4 steps and starts with (1) the definition of goals and scope, followed by (2) lifecycle inventory analysis, then (3) the actual impact assessment, that includes classification, characterisation, normalisation and weighting of each substance or resource emitted or consumed, ending with (4) the interpretation of results and a final single score (Goedkoop et al., 2008; Mota, Gomes, Carvalho and Barbosa-Póvoa, 2014). Appropriate supplier management, carbon management, political influence, dedicated Key Performance Indicators (KPIs), careful sourcing of raw materials, and product reuse and recycling are all aspects having an influence on the implementation of a sustainable SC (Gopalakrishnan et al., 2012). Moreover, OEMs can be seen as motors of SCs, establishing the bridge between customers and suppliers, acting as application points for pressures and incentives from governmental entities, customers and other stakeholders. Thus, such companies have a major role in shaping SCs regarding sustainable practices (Seuring and Müller, 2008; Barbosa-Póvoa et al., 2018).

There are different frameworks present in literature for the effective evaluation of impacts during LCA, given that this depends on the products, processes or industries that are being assessed. For instance, Carvalho et al. (2014) studied 25 different methods suitable for the index of industrial chemical processes; whereas Frota Neto et al. (2008) used an environmental index dedicated to paper and pulp sector developed by Bloemhof-Ruwaard et al. (1996). Chaabane et al. (2017) and Wang et al. (2011) considered only the Green House Gas (GHG) emissions based on reference values found in literature. Alçada-Almeida et al. (2009) used a Gaussian dispersion model to evaluate the extension of environmental impact of incinerators. Hugo and Pistikopoulos (2005) used the Eco-Indicator 99 method to develop a framework for strategic investment planning, among others (Nagurney and Toyasaki, 2003; Nagurney et al., 2007; Nagurney and Nagurney, 2010). The method of Goedkoop et al. (2008) (ReCiPE2008) is considered by the European Commission to be the most up-to-date and complete tool for environmental index assessment (Mota, Gomes, Carvalho and Barbosa-Póvoa, 2014). Most of these methods are used in optimisation models developed for problems of SC network design. In terms of limitations of the models presented, Komoto et al. (2011) reports the use of deterministic elements and the aggregation of components calculated independently, promoting error propagation. Another limitation is the difficulty in gathering information to feed the models with real data (Komoto et al., 2011).

A report of European Commission (2011) features sustainability as one of the key drivers of change for the aerospace industry. In addition to the targets fixed for emissions by 2050, the European Commission (2011) sets that aircraft should be designed and manufactured for recycling. The evolution of jet fuel price was one of the great driving forces leading to weight-reduction concerns by OEMs, mostly due to pressures from airlines. In civil aviation, the increasing application of composite materials is also driven by the high cost of jet fuel and rigid, eco-friendly regulations (Scelsi et al., 2011). As a result, aircraft become more efficient, thus implying a reduction of fuel consumption (Long, 2006; Slayton and Spinardi, 2016).

An interesting study from Scelsi et al. (2011) contributed to understanding whether the use of composites as alternative, lighter materials would be, in absolute terms, environmentally sustainable. The central question was whether such weight reduction would offset the energy-intensive manufacturing process and difficult end-of-life handling. The results showed that the use of composite materials has a highly positive impact on achieving reduction of overall emissions due to aircraft's high fuel consumption (Scelsi et al., 2011).

As seen in section 2.1, transportation costs during manufacturing are irrelevant when compared to the final cost of an aircraft (Niosi and Zhegu, 2005*a*). The same principle cannot be applied regarding sustainability concerns, as proximity within the network may lead to improved sustainable practices (Gopalakrishnan et al., 2012).

3.3.2 | Supply Chain Optimisation Methods

From the topics covered up to this part (such as supplier-buyer relations, NPD, product introduction, material and technology selection), it can be observed that the scope of this research targets the strategic and tactical levels of decision making. It is assumed that strategic level corresponds to long-term planning horizon and tactical level to a mid-range horizon, but the actual time lengths may vary from author to author (Schmidt and Wilhelm, 2000; Mota et al., 2017). Among others, these levels of decision making may include SC network design and planning, sourcing locations, operations planning and transportation network planning (Mota et al., 2017). The literature review work performed by Barbosa-Póvoa et al. (2018) revealed that optimisation methods are the techniques of choice for strategic level SC problems.

A misallocation of resources can entail severe consequences. Hence, proper design and management of the SC are fundamental in highly competitive environments, especially for companies with worldwide operations (Manzini et al., 2008). Competition is now between networks rather than firms, and decisions to be made on such complex systems have to be well-supported (Goetschalckx, 2011). For this reason, decision support systems have been widely used for SC network planning and design functions (Ballou and Masters, 1993, 1999).

Models are handy for the purposes of studying and gaining insight of complex systems, allowing a simplified representation that is not so challenging to manipulate. Most models are characterised by the transformation of known input variables and parameters into output variables and results, and there is always a trade-off between model realism and model solvability (Goetschalckx, 2011). The Operations Research (OR) body of knowledge is dedicated to solving these types of problems, following a process that includes different phases: (1) define the problem, (2) formulate the model, (3) implement the model and find solutions, (4) test model and validate results, and (5) implement the solution (Taha, 2007; Hilier and Lieberman, 2015). The normal workflow for modelling processes is to include the essential and sufficient features from the real world system, deriving the results and decisions, and improve the model iteratively (Goetschalckx, 2011).

A model for SC planning is built from different components and Goetschalckx (2011) identified nine of these dimensions to the problem: (1) time, (2) geographical locations, (3) products, (4) facilities, (5) customers, (6) suppliers, (7) transformation facilities, (8) transportation channels and (9) scenarios. The surveys carried out by Ballou and Masters (1993, 1999) report that the techniques more commonly used for SC modelling are Linear Programming (LP), Mixed-Integer Programming (MIP) and heuristic algorithms. The authors reported that these methods have been used to "solve spatial and geographical location" issues of the SC, on a strategic level, and temporal issues, on a tactical level (Goetschalckx, 2011). Either single or multiple objective optimisation models, they all are deterministic models (parameters are known with no degree of uncertainty), using the taxonomy of SC models presented by Min and Zhou (2002).

In general, mathematical models are systems of equations and expressions that describe the problem being studied and allow for different scenarios to be tested. The ones used in OR are usually formed by decision variables, constant parameters, constraints, and the objective function(s) being minimised or maximised. A subset of these models is called LP modelling, in which all the equations and expressions are linear functions. The ultimate goal of OR is to identify the optimal solution, or set of efficient solutions in the case of multi-objective optimisation (Taha, 2007; Hilier and Lieberman, 2015).

An example of a linear model is the formulation developed by Tang et al. (2013) for an aircraft wing-box SC optimisation, based on Mixed-Integer Linear Programming (MILP). The model aims to minimise the total network cost, using a deterministic model that considers fixed demand pattern and tries to answer make/buy questions, facilities allocation, location and capacities issues. On top of that, the majority of models mentioned earlier regarding sustainable SCs are based on multiple objective optimisation techniques, LCA being just one of the dimensions to be optimised.

There are many examples of the use of optimisation tools in SC modelling, multi-objective methods being a subset of these tools. As opposed to the more simple models, multiple objective methods are not meant to find the optimal solution but rather the set of efficient solutions that attain the different goals. These efficient solutions are also called non-dominated or Pareto-optimal solutions (Liu et al., 2003). Although, in many cases, this set of efficient solutions (forming the Pareto-front or curve) cannot be efficiently computed (NP-hard problems) and approximation methods are often the solution (Caramia and Dell'Olmo, 2008). The main approaches for this type of problems include the weighted-sum method (scalarisation), ϵ-constraints method, goal programming, and multi-level programming (Caramia and Dell'Olmo, 2008). Other methods for multiple objective problems exist that are based on metaheuristics algorithms (e.g., evolutionary algorithms), aiming to reach good solutions for the problem rather than optimality (Caramia and Dell'Olmo, 2008).

3.3.3 | New Product Development and Supply Chain

In this section, the issue of NPD is discussed in parallel with SC concerns. The goal here is to identify the drivers for NPD and innovation in aerospace and present the typical strategies used, their advantages and risks.

Defined first by Handfield et al. (1999), the NPD process starts with the (1) idea generation, which leads to (2) a business/technical (preliminary) assessment, followed by (3) the concept development phase, after which comes (4) the actual engineering and design phase, the final stage being (5) prototype build and ramp-up operations. For Wynstra et al. (2001), NPD is composed of (1) concept development, (2) basic design, (3) detail engineering and (4) start-up production phases. Ulrich and Eppinger (2012) added a phase prior to planning, altered the basic design phase to system-level design and introduced the testing and refinement phase before the production ramp-up. Ulrich and Eppinger's model is depicted in Fig. 3.4, and is going to be adopted for this research study since it includes a testing and refinement period that is deemed appropriate for the case. In phases 2 and 3 of NPD, customer requirements are translated into actual specifications and design solutions. This engineering design process is then divided into (1) clarification, (2) conceptual design, (3) embodiment design and (4) detail design phase. It is in the conceptual design phase that the majority of production costs are estimated (Robinson, 2012; Newnes et al., 2008; Quintana-Amate et al., 2017).

Figure 3.4: New product development process. Adapted from Ulrich and Eppinger (2012).

Glas and Ziemer (2009) and Kazerouni et al. (2011) presented some of the challenges of NPD in aerospace. The low volume of products sold means that development costs have a high impact on the price. As programmes could last for decades, each programme has its own requirements in terms of specialisation of assets, tools and infrastructures, and there is no major benefit in economies of scale. The late break-even point also creates great pressures and risks to NPD. Strict certification processes and compliance requirements have considerable influence in NPD, thus limiting the number of innovations and new technologies that can be introduced.

NPD process and new product launching are of great importance for OEMs, with considerable impact on cost, quality and competitive advantage; thus, the decision of the appropriate degree of supplier involvement must be carefully evaluated (Kazerouni et al., 2011). Petersen et al. (2005) and Johnsen (2009) define the success factors for supplier involvement in NPD programme as result of (1) appropriate supplier selection, (2) supplier relationship management, (3) supplier involved in the definition of (business and technical) targets for the project, and (4) internal capabilities. The successful supplier involvement should lead to shorter time-to-market, higher product quality and decrease the development/production costs (Johnsen, 2009).

The literature (Handfield et al., 1999; Petersen et al., 2005; Le Dain and Merminod, 2014; Zhao et al., 2014) presents a framework to help in the decision of the appropriate approach: earlier integration ('black-box'), i.e., during the idea generation phase, and later involvement ('white-box'), i.e., during the prototyping phase. This framework can be seen as a continuous axis with varying degrees of supplier integration, since suppliers may be in different stages of the NPD process. Typically, suppliers of complex and critical components or systems are considered to be of the 'black-box' type, and strategic alliances must be established, whereas suppliers of simple parts or commodities can be seen as the 'white-box' type.

Graham and Ahmed (2000) discussed the knowledge transfer to competitors through suppliers and the dangerous degrees of dependence on single partners as some of the barriers to deeper supplier integration. Thus, knowledge management is a key concern in NPD and gains even more relevance if the process of NPD crosses the boundaries of the company. Different degrees of knowledge sharing must be considered, according to the level of supplier involvement (Le Dain and Merminod, 2014). Quintana-Amate et al. (2017) anticipates the risk of "reduced availability of manufacturing experts" and "loss of [...] knowledge" after OEMs off manufacturing functions, suggesting that aerospace is in need of knowledge management support systems. Interestingly, Mazzola et al. (2015) introduces the concept of 'supply chain of innovation' as a tool for NPD for the flow of Intellectual Property. By contrast with other industries (e.g., biotechnology), aerospace is not characterised by large volumes of scientific production and technology licenses but rather by secrecy in processes (Niosi and Zhegu, 2005*a*).

In the light of the strategic management body of knowledge, there are four generic 'strategic directions' for a company seeking diversification and growth, depending on their market and product conditions. These directions form the Ansoff's matrix: a framework used to generate corporate strategies from the available information, for a company to endeavour new or existing markets using new or existing products/services (Johnson et al., 2014). Here, the development of new products is a suitable direction to pursue if OEMs are aiming to attend existing markets and is not feasible to consider further market penetration. It can be done either by modifying existing products into a new and updated iteration or creating entirely new products/services. However, the author is swift in highlighting the costs and risks associated with NPD, namely the need for new technologies and capabilities and increased project management concerns (Johnson et al., 2014).

As discussed by Niosi and Zhegu (2008), industries/products are born from the idea of 'an original innovator', then replicated by followers and the appearance of different iterations and designs. This very same principle can be transported for the evolution of industries, especially with fierce competition fighting to increase market shares. In business environments, innovation can be of either process or product and occurs when there is a transformation of knowledge into some commercial application (Trott, 2005; Johnson et al., 2014). Frequently, product innovation is used with disruption and differentiation intents; whereas process innovation is used after a given period and a "dominant design" was achieved, or when reduction of costs is an imperative (Utterback and Abernathy, 1975; Johnson et al., 2014).

The study by Montoya-Weiss and Calantone (1994) helped in identifying the relevant factors for new product performance, segmenting them in four main groups: (1) strategic factors, with product advantage leading; (2) development process factors, with focus on protocol; (3) market environment factors, where market competitiveness comes first; and (4) organisational factors, highlighting the internal/external relations. A later study by Cooper and Kleinschmidt (1995) proposed that new product performance depends on (1) the internal process of NPD, (2) organisation of NPD programme, (3) NPD strategy, (4) culture for innovation and (5) senior commitment. Another key issue in NPD is the time-to-market, for obvious reasons: shorter periods of development and time-to-market allow to beat the competition and gain market share (Trott, 2005).

3.3.3.1 | Product Introduction Process (Scale-up)

As discussed earlier, companies in highly competitive environments have to launch new products in order to thrive and gain market share. For instance, Tang et al. (2009) presented Boeing's production strategy of outsourcing roughly 70% of development and manufacturing activities in an attempt to reduce time-to-market and decrease development costs by relying on multiple suppliers' knowledge. It will be more clear ahead why an appropriate New Product Introduction (NPI) process must be defined, avoiding problems associated with scaling-up the process or other negative impacts on the company's performance.

Scale-up and ramp-up are terms commonly used interchangeably. Even though, only the first actually means NPI, while the latter represents an increase in production volume. The final stage of the NPD is the production scale-up, characterised by the introduction of the product design into full-scale production (i.e., industrialisation) (Javadi et al., 2016). Both these elements are major cost drivers, with some programmes requiring investments of more than $10 billion USD (Schuh et al., 2005; Isenberg, 2012). Thus, an adequate process of product introduction is critical to avoid compromising all previous work of NPD and to ensure that a new product effectively fulfils its goal of generating profit (Bellgran and Säfsten, 2010; Javadi et al., 2013, 2016).

The stages of NPI considered for this research are presented in Fig. 3.5. The end of NPI occurs when the initial goals are achieved (i.e., production rate or costs). Surbier et al. (2013) characterises NPI phase as follows: (1) poor initial knowledge about product/process, (2) low production rate, (3) high cycle times, (4) low capacity, (5) high demand, (6) high number of disturbances and (7) lack of reliability. The production ramp-up stage is also very prone to mistakes and disturbances that result in the unintended consequences (e.g., higher production times and quality issues). These disturbances can be grouped in different source areas related to (1) product, (2) production system, (3) supply chain, (4) quality, (5) resources, (6) personnel and (7) design product interface (Javadi et al., 2016).

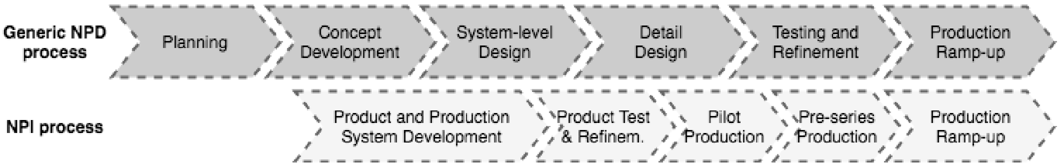

Figure 3.5: Stages in product introduction process. Adapted from Javadi et al. (2016).

Among the critical factors to be considered before ramp-up are (1) the fit between product and process, (2) learning and training and (3) the involvement of manufacturing in the process. During the ramp-up process, critical factors are (1) the performance of existing production, (2) the time for testing, calibration and maintenance, (3) the breakdown of equipment and (4) the existing supplier relations (Berg and Säfsten, 2005; Johansen, 2005; Javadi et al., 2016).

In industries with products of high complexity, the process of designing production systems and the scale-up is itself more complex; thus resulting in higher risks of failure and profit loss (Berg and Säfsten, 2005; Bellgran and Säfsten, 2010; Javadi et al., 2016). The following decision variables introduced by Wheelwright (1984) and Berg and Säfsten (2005) are crucial in NPI process: "capacity, facilities, technology, vertical integration, workforce, quality, production, materials and organisation". In addition, Tang et al. (2009) presented six risk factors in the 787's SC, namely the technology, supply, process, management, labour and demand, that resulted in unintended consequences, such as delays due to lack of knowledge and transparency of suppliers' operations.

On top of that, product design is another impacting factor of the industrialisation process. The literature (Adler, 1995; Lakemond et al., 2007; Javadi et al., 2016) refers the importance of the design/manufacturing interface for the overall performance of the system and the success of new product introduction. The concepts of Design for Cost (DFC), for Value (DFV), for Manufacture (DFM), for Assembly (DFA), for Test (DFT), for Maintenance (DFM), for Reliability (DFR) and for Environment (DFE), among others, are aspects to be considered during the design phase, and trade-offs must be made to balance all the different and conflicting goals (Ullman, 2010). In aerospace, most manufacturing processes are external to OEMs; thus the involvement of suppliers in the process is crucial. Much like the other phases of product development, the earlier involvement of suppliers is vital to reduce production disturbances and to minimise risks of faulty products (Maffin and Braiden, 2001). Whether it is the production of a whole new product or a modified version of an existing one, achieving efficiency in start-up and operations can be done through extensive prior planning and appropriate control (Bellgran and Säfsten, 2010).

On account of high costs associated with new aircraft development programmes, it is essential to understand how these may vary in the long run of a manufacturing line. Through an empirical study, Wright (1936) was able to suggest the concept of 'learning curve' where the accumulated production quantity has a direct impact on the cost. Thus, in general terms, the higher the number of repetitions of the production cycle, the lower the unitary costs, and profitability of the same model is higher.

The learning curve was thought for the aerospace industry, associated to the phenomenon of learning processes from the manufacture of new aircraft models (Wright, 1936; Baloff, 1966). However, Benkard (2000) argues that the effect of human capital accumulation is not one way only since the opposite can also occur, forging the idea of 'organisational forgetting'. Even though, there are differences in military and commercial aerospace programmes: the first characterised by the continuous production of the same models, and the latter subject to uncertainty in orders. This continuous production enables the learning effect, which may not happen for commercial OEMs. Benkard (2000) refers that experience is accumulated in workers but outsourcing, turnover and layoffs could result in the loss of it.

The moment of product ramp-up is where most development costs are concentrated, making it a key variable for fast investment recovery. Hence, the shorter this phase, the shorter the time-to-payback (Ball et al., 2010; Surbier et al., 2013). Getting products to market faster than competitors may result in higher profits. In scale-up processes, the production rate is grown from small in-lab produced batches to full-scale volume production as confidence both in customers and suppliers is consolidated (Wheelwright and Clark, 1992; Terwiesch and Xu, 2004). Technology transfer and volume ramp-up, in Fig. 3.6, make up the transition steps of development to volume production (Li et al., 2013). The US Department of Defense (1985) led the knowledge diffusion in this regard, publishing a manual for the transition of development into production and with the elicitation of main risks (Bassetto et al., 2011). In

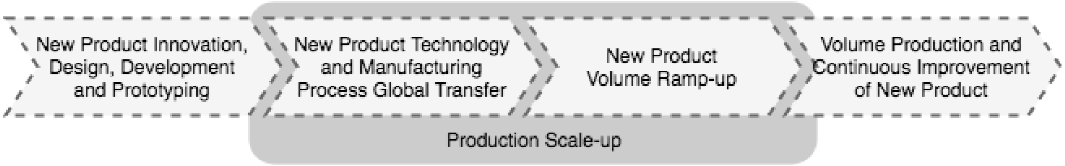

Figure 3.6: Production ramp-up phases. Adapted from Li et al. (2013).

this transition, there is usually a dislocation between development facilities and manufacturing sites, and this involves careful adaptation to new cultural, facilities and infrastructural conditions. In addition, the "complex collaborative inter-firm manufacturing supply networks" formed by OEMs and suppliers have to be managed accordingly (Li et al., 2013). The potential risks of supplier involvement in NPD may be split into five partitions: (1) loss of (proprietary) knowledge/skills, (2) lock-in to suppliers technology, (3) high relationship costs, (4) slow down of NPD process, and (5) different goals and objectives, with diverging levels of commitment (Echtelt, 2004).

It has already been shown the strain that NPD and NPI poses on SCs. Different levels of supplier involvement could be adopted by OEMs, according to the needs and complexity of each part/system. By adopting a posture of systems' integrators, OEMs transfer "responsibility for advancing the technology" to the suppliers of subsystems (Reed and Walsh, 2002). This transfer of responsibility raises questions about suppliers' ability to stay on the cutting edge of technological innovation, or whether they can develop the necessary capabilities. Suppliers are demanded to look towards the future to understand and learn future technology needs, in a process called technology lookahead (Reed and Walsh, 2002). Thus, the development of suppliers is crucial, so that in the long run their early involvement in NPD can generate new technologies and improve new products (Reed and Walsh, 2002). A competitive advantage can be achieved if a technologically-advanced supply base is maintained (Handfield et al., 1999).

In aerospace, the development of a new aircraft design or production programme is subject to several factors: (1) commercial and/or financial feasibility, (2) technological feasibility, (3) manufacturing facilities (capabilities), (4) political and/or environmental feasibility, and (5) other lessons learned from past aircraft programmes. The commercial/financial viability can be influenced by market potential, cost and time of development, workforce capabilities, production investment and potential return on investment (ROI), whereas the technological feasibility is dependent on configuration selection, structures, flight controls, materials, aerodynamics, propulsion, systems and manufacturing (Roskam, 1985).

Isenberg (2012) compared the ramp-up management process both in aerospace and automotive industries, for the following ramp-up drivers: (1) lifecycle, (2) frequency of ramp-up, (3) commonality of products (technology & design), (4) product complexity, (5) certification time, (6) product variance, (7) product architecture and - technology, (8) production technology, (9) methods, processes and tools, (10) industrial set-up, and (11) verification & validation. Although there are distinct differences between these industries, the automotive industry has a highly developed ramp-up process that can be considered the baseline for aerospace manufacturing reality. One example from the automotive industry is the standardisation and modularisation, that is known to be a ramp-up enabler and which has no direct copy in aerospace since almost every product line is different (Isenberg, 2012). Elstner and Krause (2012) studied the need to consider ramp-up process earlier in the development stages, providing the literature with a methodology for risk identification and minimisation. The influencing factors of the ramp-up phase can be split into four categories: (1) degree of innovation, of market and technology, (2) complexity, of product and/or process, (3) maturity of product and/or process, and (4) supplier integration (Elstner and Krause, 2012). To avoid these risks, Isenberg (2012) suggested improvements to close the gap between ramp-up practices of automotive and aerospace. The key activities for product deployment consist of product development, prototype production, preproduction, pilot run/production tests, series ramp-up and, finally, series production. As for resource fitness, it requires facility design, facility realisation, proving of processes/implementation, facility ramp-up and the continuous improvement of the process (Isenberg, 2012). Specifically, OEMs should focus on assembly strategies and technologies (modularity), integrated methods, processes and tools for design and manufacturing, SC planning and controlling, cabin customisation and installation, technical change management, and flexible jigs and tooling. (Li et al., 2013; Isenberg, 2012).

3.4 | Summary of Chapter 3

This chapter addresses literature on the more technical aspects of the research, since the development of a model requires sound theoretical foundations.

The use of composite materials, especially of polymers, has been growing and suiting applications have been finding their way for lightweight commercial products. Thermoplastic and thermosetting polymers are common in aerospace applications, and the properties of each have to be taken into account. Manufacturing processes based on four distinct forming techniques are studied in detail, and emphasis is put on OoA technologies as potential cost reduction factors. The topics of composites-waste flows and recycling also deserve particular attention due to current concerns of sustainable NPD.

The history of costing tools used in projects or products is reviewed. Some tools used for cost estimation in manufacturing processes are studied, and typical cost factors are identified. It is also noted that there is a strong link between cost estimation and the design of product and process, where it is verified that these should be taken into account mutually. In the end, design decisions must consider a holistic approach.

Last, some aspects of SCM are also revisited. The importance of including sustainability concerns in organisations' performance measures led to the 3BL framework. The strategic-tactical level of decision making on which the problem is positioned points towards optimisation techniques - a common set of tools used in SC problems. Additionally, the fundamental concepts regarding NPD and NPI are presented, such as main drivers, strategies, disturbances and critical factors that affect these processes.

In the next chapter, a more concrete definition of the problem is presented and a SC optimisation model is proposed using sustainable performance measures.

4 | Problem Definition and Formulation

Previous chapters provided the context and theoretical foundations necessary for the development of an optimisation model. The literature review carried out grasped the importance of using performance measures which promote sustainability across several dimensions. This chapter discusses the problem with more detail and proposes the referred sustainable SC optimisation model for the aerospace industry.

The present chapter has three sections. The first section for the actual definition of the problem that includes the model framework summarising the workflow and more information about each objective. Section two starts with the modelling assumptions and presents the proposed mathematical formulation, including indexes and sets, model variables, constraints and objective functions. The last section gives a brief summary of the contents discussed.

4.1 | Problem Definition

The purpose of this section is to detail and frame the problem, going over a context and presenting a description of what is considered in the mathematical formulation. A model framework is also presented ahead, along with a description of each model objective.

As mentioned before, this work is in line with the research group IAMAT on the pursuit of a framework to evaluate and decide on the appropriate manufacturing process for the aerospace composites SC. By undertaking a holistic approach not focused only on economic measures but also environmental and social - and after proper application to a testbed -, it is intended that this framework can be generalised to other mobility industries (IAMAT, 2017). As such, this work builds on top of previous research carried out by the group targeting the same objectives, namely the work of Santos (2017) and Marques (2018), whose data collection is instrumental in developing and testing the model.

The four forming processes of concern are (1) TA, (2) VARI, (3) VBO and (4) TS and are illustrated in annexed figures A.1, A.2, A.3 and A.4 (IAMAT, 2017). Finished products resulting from each process are considered equal across the manufacturing processes, and any differences in dimensions, characteristics and performance of the products are negligible. Even though the four alternatives are under study, the industrial partner - Embraer - currently only employs the TA, whereas other processes are developed in laboratory with the research partner - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (Institute of Science and Innovation in Mechanical and Industrial Engineering) (INEGI).

The testbed model being used by IAMAT is showed in Fig. 4.1. This testbed formed by the set of stringer and skin is considered to be representative and a building block of most complex aerostructures (e.g., wings, fuselage, or flaps). Even though the testbed exhibits a "T" transversal profile, only the base skin is considered on this research, so as to enable the comparison and validation with the work of Santos (2017) and Marques (2018).

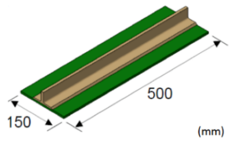

Figure 4.1: Testbed. Source: IAMAT (2017).

The reference aerostructure being considered ahead for the case study follows a series of scale-up principles and relations introduced by Marques (2018), which are better described in the next chapter. Nevertheless, a general scale-up multiplier is derived from the relation between the area of one testbed and the area of one reference aerostructure, taking the value of 1200, according to dimensions summarised in table 4.1.

Table 4.1: Dimensions of testbed and reference aerostructure

	Testbed	Reference
Width	0.150 m	5 m
Length	0.500 m	18 m
Thickness	0.004 m	0.004 m
Area	0.075 m^2	90 m^2

The model is intended to be general and adaptable to different problems. However, it hardly can be dissociated from the actual context of the original problem.

Ideally, the SC network design includes multiple suppliers with different characteristics, several locations for installing facilities and a variety of transportation modes, enabling the model to select the optimal conditions. In this case, the sequence of SC activities is very typical: materials are purchased from suppliers, transported to warehouses (if available) or factories for transformation into finished products and transported again to warehouses (if available) or to customers/markets. For the aerospace case study to be presented ahead, the focal company is a 'Tier 1' supplier and the market is the OEM (and parent company). A graphical representation of the SC network structure considered for the problem and respective flows is shown in Fig. 4.2.

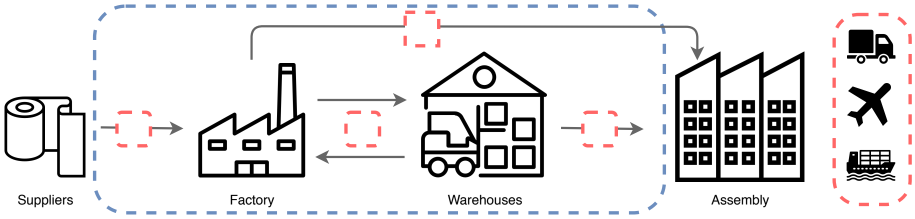

Figure 4.2: Example of a network structure. Adapted from Mota et al. (2017).

Thus, the aforementioned SC requires raw materials (and support materials, if needed), origin and destination entities (e.g., suppliers, warehouses, factories and markets), resources and technologies for transforming materials, and transportation modes (e.g., truck, plane, boat).

The problem could be summarily stated as follows:

Given:

- A superstructure of interacting entities and respective existing or potentially new geographical locations, composing the supply chain network;
- A set of resources, materials, and time constraints;
- The supply and production capacities;
- A set of alternative manufacturing processes, well characterised and with durations of productive activities;
- The bill of materials, time and resources needed for manufacturing;
- The demand for products being produced;
- A transportation network and transportation means available;
- A fixed time horizon;

- The distance between all points/entities;
- A set of available technologies for manufacturing;
- The fixed/investment and variable costs associated with the whole network (i.e., materials, suppliers, factories, resources, technologies, transportation network, hubs and modes, etc);
- The environmental impacts associated with the whole network (i.e., materials, suppliers, factories, resources, technologies, and transportation activities);
- The social characterisation of the manufacturing processes and transportation activities;
- The initial inventory levels;
- The initial fleet levels;
- The initial resources at each entity.

Determine:

- The network configuration, in terms of which and how many facilities to open, maintain or close;
- The transportation network structure and the optimal mix of modes to adopt;
- The optimal manufacturing process and technologies to be selected;
- The product flows transported between supply chain network entities;
- The total cost of the solution;
- The total environmental footprint of the network;
- The total social impact.

In order to:

- maximise Net Present Value;
- minimise Environmental Impact;
- minimise Social Impact.

4.1.1 | Model Framework

After defining and framing the problem, this section presents a framework that allows a general and global view of how the model is supposed to work.

As referred in the literature review, the strategic-tactical nature of the problem points towards the use of optimisation models, which enable decision making considering a SC perspective. The mathematical formulation presented is an adaptation from the MILP model proposed by Mota et al. (2017) for SC network design problems.

Several steps are required before having on-demand results and figures for analysis, always starting through the process of collecting and treating input data for each objective. With data that is available and considerable knowledge of the problem the mathematical formulation can be constructed and implemented. This general workflow is depicted in Fig. 4.3.

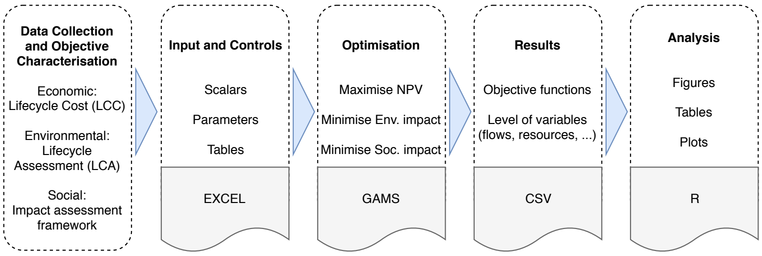

Figure 4.3: Model framework.

4.1.2 | Model Objectives

Considering the endless set of activities that SCs undergo to satisfy demand and customer needs, the use of performance measures is required to find the optimal network structure. This subsection describes the three performance measures to be included in the model: economic, environmental and social.

Economic objective

This section presents the economic objective to be included in the model. As discussed in previous chapters, economic metrics are the most common performance measures found in literature and of the utmost interest for profit-seeking enterprises.

Following the topics discussed in section 3.2 (Cost Estimation Techniques) and based on the cost structure by Xu et al. (2006) presented there, this economic objective function targets only the manufacturing and the marketing stages of the LCC. This modelling decision has to do with the lack of information and knowledge regarding those other stages, such as design and disposal, and to avoid building great discrepancy between objective functions since those stages would be characterised in more detail for the economic measures rather than environmental and social. Even though, other costs could be easily added to the objective function if that was the case.

The economic objective function presented here is based on the Net Present Value (NPV), which is the difference between incoming and outgoing cash flows over a period of time. NPV is a common metric if an economical evaluation is performed for non-coincident time periods, meaning the value of cash is not the same at all times and needs to be discounted/normalised for this reason.

The general formula for NPV is given by:

$$\mathrm{NPV} = \sum_{t=1}^{T} \left(\frac{NetInflow_t}{(1+r)^t} \right) - StartUpInvest \tag{4.1}$$

where $NetInflow_t$ is the net cash inflow in period t, r is the discount rate, t is the number of periods and $StartUpInvest$ is the initial capital investment.

The structure of the economic objective function detailed ahead is based on Mota et al. (2017), and especially suited for the case of IAMAT (2017), even though it can be generalised for different problems.

Environmental objective

In addition to the economic performance measure, the environmental metrics are of increasing importance for academics and enterprises, as shown in the previous chapter. Accordingly, this section introduces the environmental measures being used. The LCA method is briefly described and is followed by the introduction of most relevant indexes, sets and variables. All of this is useful for the environmental objective function which is detailed after, with an explanation of each equation and feature.

LCA

The LCA method was introduced earlier as one of the most common techniques to assess the environmental impact, thus being used in this work as well. The method of Goedkoop et al. (2008) (ReCiPE2008) is used to perform the LCA and determine the environmental impact, following the work of Mota et al. (2017) and Santos (2017) with similar goals in terms of impact assessment. As reviewed earlier, this method is considered by the European Commission to be the most up-to-date and complete tool for environmental impact assessment, allowing for the assessment both on midpoint and endpoint levels (Mota, Gomes, Carvalho and Barbosa-Póvoa, 2014).

In the ReCiPE method (Goedkoop et al., 2008) several midpoint impact categories are defined as intermediate characterisation points that can be quantifiable. The values from all midpoint categories can then be further converted and aggregated into endpoints that are more related with actual environmental consequences: (1) damage to human health (HH), (2) damage to ecosystem diversity (ED), and (3) damage to resource availability (RA). Some aspects are conditioned to subjective judgement when performing an environmental assessment, and the ReCiPE method also allows for the possibility to model cultural beliefs and perspectives with the possibility of selecting from the Hierarchist (H), the Egalitarian (E) and the Individualist (I) perspectives, which model different time-frames (Goedkoop et al., 2008).

Even though it may be sometimes difficult to execute an exhaustive LCA, especially due to scarcity of real data, there exists dedicated software to support in the task of impact estimation (Eskandarpour et al., 2015). One example is SimaPro, a known leading tool to support the LCA process and promote evidence-based sustainable performance management (PRé, 2018). Using SimaPro software allows to carry out the LCA based on ReCiPE, thanks to the complete database with informations from resource depletion, energy consumption and GHG emissions, among other indicators, associated with the materials and processes that are the focus of research.

Social objective

The third and last objective function encloses the social aspects of SC performance, known as being the least studied and poorly characterised metric of the 3BL sustainable performance measures (Seuring, 2013; Popovic and Kraslawski, 2015; Barbosa-Póvoa et al., 2018). Consequently, this section is meant for a dedicated literature review in order to derive a basic framework for social impact assessment and to be included in the social objective function.

Social Impact Framework

The poor characterisation and less frequent use of social measures to manage performance in SCs is the motivation for the development of a framework that encompasses this sort of aspects. After carrying out a more thorough review of specialised literature, several indicators that could represent the social dimension are identified. For instance, Singh et al. (2016) refers the (1) 'employee well-being', that includes training hours, turnover ratio, number of accidents and job satisfaction factors; (2) 'customer well-being', that includes customers' satisfaction, warranty and other factors related with product/service; and (3) 'community well-being', that includes non-compliance, child labour and salary factors, as social performance measures. Mota et al. (2017) focuses more on macro-economic factors (such as job creation and GDP) to evaluate the social dimension since their model is targeting network design problems and facilities' location.

Dočekalová (2013) and Popovic et al. (2018) also mention a series of indicators that could be used if all forming processes had previous industrial application and historical data could be collected (being considered lagging indicators), such as the time lost with health and safety incidents (e.g., number of accidents or injuries) or amount of training provided/required for each technology. Although, this information is not available at the time of decision on the actual forming process. The same applies to guidelines provided by Global Reporting Initiative (2014), where the majority of indicators would fit best in an *a posteriori* evaluation. As Henao et al. (2017) discusses, the majority of social performance indicators are 'too general' and 'high-level', and these are the most complex to objectively assess and measure because they usually are qualitative and non-comparable across contexts.

The concept of Social Lifecycle Assessment (S-LCA) was coined from the well-known LCA, including the same phases and methodology (Popovic and Kraslawski, 2015). This technique was also reviewed as an attempt to include in the social objective function, yet it was found that measures would suffer the same problem of being too general and having to assign weights to aggregate different measures with different units (Popovic and Kraslawski, 2015). Nevertheless, the same idea of deriving a single score is useful for the purpose of constructing a framework, as long as those are not an aggregation of different measures and weights are not arbitrarily assigned.

Guadix et al. (2015) argues that factors such as 'safety, hygiene, and ergonomics' or 'job satisfaction and work intensification' may lead to psychosocial risks for employees. On the other hand, EU-OSHA (2011) focuses on transport sector and identifies 'vibration, painful positions, carrying/moving heavy loads, noise, high and low temperatures and inhalation of smokes/fumes' as more likely to have health implications than in other sectors, whereas the exposure to chemicals is less prominent. Even though both authors are not focused on manufacturing industries, it may be useful to transpose the same principles to a manufacturing environment. Moreover, Varghese et al. (2018) studies the risks to occupational health of employees due to heat exposure in manufacturing industries, concluding that a correlation exists between exposure to heat and 'impaired worker health and safety', even though most assessment techniques identified by the author are mostly based on *a posteriori* evaluation. Another matter of concern is the exposure to toxic and carcinogenic materials, as presented by Bloor et al. (2000) in the case of seafarers, and which is considered a reasonable indicator for workers handling chemical materials such as resins.

The following framework presented by Henao et al. (2017) in figure 4.4 is interesting to summarise the findings in terms of literature related with social impact assessment, despite this research being limited to just occupational health and safety factors.

Several authors (Popovic and Kraslawski, 2015, 2017; Popovic et al., 2018; Stoycheva et al., 2018; Nilsson and Vänje, 2018) refer the importance of occupational safety, ergonomic workplace and workers' health to the manufacturing environment. Given the difficulty of characterising all social implications that could be involved in SCs, and considering a compromise must be made, this research is framed within the employee well-being factors and related aspects of occupational health and safety.

Considering the main goal is to effectively select the most favourable forming process, the framework is built to emphasise the differences between manufacturing processes in most relevant categories in terms of social impact. For this reason, this research makes use of simple qualitative assignments to indicate the absolute difference/distinction of a given process in the named measure, representing if the process has negative, neutral or positive social impact on that same measure. The measures are also selected based on findings from literature and on their relevance. The summary of these measures is

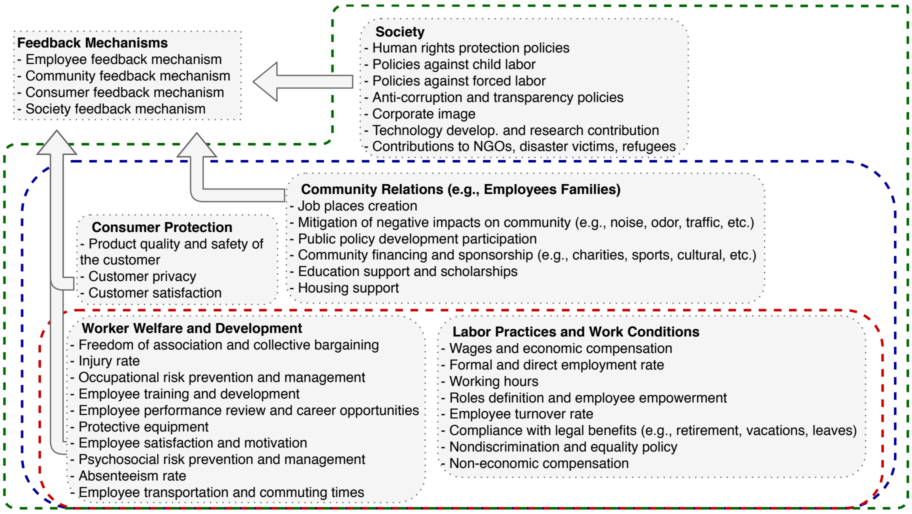

Figure 4.4: Social performance metrics framework. Source: Henao et al. (2017).

presented in table 4.2.

Table 4.2: Social impact measures

	Measure	Value	Reference
1	Exposure to heat	{-1,0,+1}	[1] [2] [5] [8]
2	Exposure to cold	{-1,0,+1}	[1] [2]
3	Exposure to micro/small particles/fibres	{-1,0,+1}	[1] [2] [4]
4	Exp./inhalation of hazardous/toxic gases	{-1,0,+1}	[2] [4] [5] [6]
5	Exposure to noise	{-1,0,+1}	[2] [5] [6]
6	Exposure to high-pressure environment	{-1,0,+1}	[5]
7	Exposure to mechanic hazards	{-1,0,+1}	[1] [8]
8	Long-period standing	{-1,0,+1}	[2] [8]
9	Handling movements	{-1,0,+1}	[2]
10	Exposure to hazardous/toxic materials	{-1,0,+1}	[1] [2] [4] [5]
11	Man-hours per part (labour-intensive)	{-1,0,+1}	[3] [7]
12	Additional finishing (open mould)	{-1,0,+1}	[1]
13	Rework, waste disposal	{-1,0,+1}	[1]

[1] US-OSHA (2011), [2] EU-OSHA (2011), [3] Dočekalová (2013), [4] Oregon OSHA (2014) [5] UK-HSE (2014), [6] Barclays (2015), [7] Henao et al. (2017), [8] Varghese et al. (2018)

From the review performed and to the best knowledge, no framework exists to classify and characterise composite materials manufacturing processes and the supply chain as whole on the social impact. As such, the framework is derived for further use in the optimisation model. It must be stressed that this methodology assumes all measures of equal importance, otherwise it would be necessary to define weights for the aggregation into a single score.

All aspects not contributing for the distinction of the processes or considered neutral are disregarded, such as the production of the carbon fibres or the resins. Even though smaller differences may exist from the varying constituents.

4.1.3 | Adaptations from original model

For this research, several modifications are made from the base MILP model by Mota et al. (2017). The inclusion of a more detailed manufacturing stage with possibility to select one out of four alternative forming processes, alongside a breakdown in manufacturing activities including durations and possibility to selectively allocate resources/technologies to activities are the most important differences. It is also included the possibility for varying the batch size for each activity. It is worth mentioning that technologies are included in resources instead of a separate 'resource', and most constraints are modelled as balance equations of flows and stocks. The original model includes reverse flows and remanufacturing, which are left out of this version. The addition of a rejection rate in the demand equation to account for quality issues. Other aspect worth mentioning is the inclusion of parameters to change the scale-up relationships from laboratory to industrial environment and variable batch size for each manufacturing activity. The introduction of a basic form of learning curve to account for productivity changes throughout the time and the possibility to scale-up the Bill of Materials (BOM) right from laboratory data are among the differences to the original version. Social measures and objective function are entirely different, yet based on the original environmental objective function.

4.2 | Mathematical Formulation

The mathematical formulation for the proposed model is described in the present section. Starting with the introduction of general model assumptions, followed by the description of indexes, sets and decision variables used. General constraints of the model are explained right after, including the more relevant parameters of those equations. Objective functions are presented after the general constraints and the respective auxiliary variables are described before the equations.

Even though most parameters are described along each equation, a more complete and compact version of the model is included in Appendix A, including all indices, sets, parameters, variables and equations of the proposed model.

The convention adopted and being used throughout the section is: indexes are expressed as subscripts by *lower-case* characters in Variables and parameters; sets are represented by a *Capital letter* accompanied by a descriptive subscript; the first character of parameters starts with *lower-case* and Variables start with *Upper-case*; within the general variables, continuous variables are defined by two characters at most, whereas integer variables are expressed in more self-explanatory terms (e.g., 'Add', 'Cut', 'Sell', etc.); binary variables are expressed in *greek letters* accompanied by the respective subscripts; for the objective functions, *greek letters* are also used without subscripts to represent specific sets and indexes of these functions, with *lower-case greek character* representing indexes and *Upper-case greek character* for the respective full set.

4.2.1 | Model Assumptions

A few compromises and assumptions need to be made if a model is to represent a much more complex reality. This section is reserved for enumerating the general assumptions and simplifications made in order to develop the model. These assumptions prove even more critical if the problem is surrounded by uncertainty and there is no guarantee if given parameters of interest can be estimated with sufficient accuracy. Aerospace industry is characterised by secrecy in their processes, and in particular those not yet consolidated, due to the competitive environment.

Having three objective functions, it is important to set the boundaries of analysis for each one. Economic objective function targets only the manufacturing and the marketing stages of the LCC, which include costs with material, facilities, production and distribution. Distribution costs include everything from suppliers' outbound flows down to OEM's inbound flow. Similar boundaries apply to the environmental and the social objective functions, even though with more simplifications for aspects related to transportation.

The production level is assumed to be equal to demand, and this demand is considered unchanged over time. Not having access to information of how warehouses and inventory system work in the aerospace industry and for the case of CFRP materials, these are modelled merely as a function of unit cells with all costs and impacts associated to these. There are also no requirements of safety stock, and it is assumed that ruptures of inventory never occur.

Even though the model aims at being a generic formulation, some modelling decisions require a certain level of specialisation. One example of this is the formulation for the manufacturing process which is based on the problem described before. Here, only one forming process can be selected per factory, not including the possibility of using different technologies to produce distinct parts. Another example is the temporal scale included in the model, which is uniformly discretised and specified in years but could be adapted for different periods.

Without data for a real aircraft part, the finished product considered in the model is the reference aerostructure described earlier, which results from the scale-up of the testbed. It is assumed that the finished product does not differ depending on the process since technical and engineering requirements need to be met.

It is assumed that deliveries of material are instantaneous and that the factory is not liable to disruption of supply. Besides, no lead times of any sort are considered, neither transit times nor set-up times. It is also assumed materials have no expiry date and there are no restrictions on shelf-life.

Specificities of cold SC and temperature monitoring are only included with the use of two types of transportation: with and without cooling. No additional aspects regarding handling cold materials are considered.

Additional assumptions and modelling options are described throughout the description of equations and whenever this is deemed convenient.

4.2.2 | Indexes and sets

Let L be the set of locations where entities (i.e., suppliers, factories, warehouses, ...) are established or can be potentially located. Let $i = (1, 2, \ldots, n)$ be the index denoting these locations, graphically represented as subscript in parameters or variables whenever these are meant for specific entities. Moreover, $j = (1, 2, \ldots, n)$ can be used to designate an additional location interacting with location i. Flows from i to j use these as 'coordinates', and the set of all connections between two points is represented by N. Flow from i to j represents an outbound flow from i, while from j to i represents an inbound flow. Subsets by type of entity are also defined such that $L = L_{sup} \cup L_f \cup L_w \cup L_c \cup L_{air} \cup L_{port}$, where L_{sup} denotes the suppliers, L_f the factories, L_w the warehouses, L_c the customers, L_{air} the airports, and L_{port} denotes the seaports. To account for intercontinental transportation, entities can also be grouped by region, such that $L = L_{REG1} \cup L_{REG2} \cup L_{REG3}$. For the purpose of computing handling costs, the set L_{mtp} is used to denote all points where occurs transfer of material and, therefore, handling costs associated.

As mentioned, N represents the set of all connections. N_{NET} represents the allowed connections. And the nomenclature following this structure $N_{OUT_{i/x}}$ or $N_{IN_{i/x}}$ represents the connections of flows of material x that can be either rm for raw materials or fp for final products from or into location i. For inter-continental connections, only possible through boat or plane, the set N_{inter} is used, while N_{intra} is used for intra-continental connections following the same rationale.

Let Z be the set of transportation modes available for use and $z = (1, 2, \dots, n)$ be the index denoting these modes. Then $Z_{truck} \cup Z_{plane} \cup Z_{boat}$ are the subsets that form the set Z, representing road, air and maritime transportation modes, respectively. Additionally, $Z = Z_{cool} \cup Z_{nocool}$ represent the modes with and without cooling systems, respectively. The set Z_{fleet} is used to distinguish vehicles that are not outsourced.

Consider R the set of resources available to be used in manufacturing and $r = (1, 2, \dots, n)$ the index that represents these resources. The resources can be divided in labour or production technologies, such that $R = R_{labour} \cup R_{tech}$.

Regarding the time units for the model, two different levels are considered: monthly and yearly. The index t is used for months and y is used to represent the years, such that T and Y represent the whole set of months and years, respectively. In the manufacturing processes, activities are used as to allocate resources, materials and duration. These activities use the index $a = (1, 2, \dots, n)$.

Let M be the set of materials used by the model, where $m = (1, 2, \dots, n)$ is the index used as subscript in parameters or variables to refer each material. Alternatively, $p = (1, 2, \dots, n)$ is the index used when the material is specifically referring to finished products. There are subsets such that $M = M_{raw} \cup M_{support} \cup M_{product}$ or even $M = M_{cool} \cup M_{nocool}$. The subset of materials for production (excluding finished products) is given by $M_{mat} = M_{raw} \cup M_{support}$.

4.2.3 | Decision Variables

The main goal of every optimisation problem is to find the optimal or an efficient setting of the decision variables so as to maximise/minimise the objectives. This problem has three types of decision variables: the continuous variables that can take any positive value, the binary variables to define if a setting is active or not, and the integer variables that allow to increment or decrement other variables in integer values. The integer variables used in this case are auxiliary ones and purely a matter of modelling style. All these are summarised in table 4.3. There are other (auxiliary) variables of all types with respect to the different objective functions and those are presented in the respective sections.

4.2.4 | General Constraints

This subsection describes the general constraints of the model, which are common to the several objective functions. In a broad perspective, these equations are related to demand, manufacturing, the balance of material flowing in and out of the entities, the balance of resources throughout time, entities' capacities, and all aspects regarding transportation and fleet ownership.

Demand

The fundamental principle of the model is that demand must be met since this corresponds to a model for internal planning and decision making.

Table 4.3: Decision Variables

Continuous variables:	
$F_{z,i,y}$	Fleet composition (trucks z owned) and assigned to i in period y
$P_{i,p,y}$	Production of p in location i in period y
$PO_{i,j,m,y}$	Material m ordered from i to j (purchase order) in period y
$R_{r,i,y}$	Amount of resources r hired/owned for location i in period y
$S_{i,m,y}$	Amount of inventory (stock) of m in i in period y
$T_{z,i,j,y}$	Number of trips of mode z from i to j in period y
$Tr^{period}_{z,i,y}$	Trucks z owned and assigned to i in period y
$X_{i,j,m,z,y}$	Outbound flow of material m from i to j using mode z in period y
$X_{j,i,m,z,y}$	Inbound flow of material m to i from j using mode z in period y
Binary variables:	
Θ_i	1, if entity in location i is open; 0, otherwise
$\zeta_{z,y}$	1, if transportation mode z is used in period y; 0, otherwise
Ω_p	1, if forming process for product p is selected; 0, otherwise
Integer variables:	
$AddR_{r,i,y}$	Amount of resources r hired/bought for location i in period y
$CutR_{r,i,y}$	Amount of resources r fired/sold for location i in period y
$BuyT_{z,i,y}$	Trucks z bough and assigned to i in period y
$SellT_{z,i,y}$	Trucks z assigned to i sold in period y
$CellsOpen_{i,y}$	Amount of cells open at location i in period y

Equation 4.2 establishes that total inbound flow of customers/markets must be equal to their annual demand, which is the sum of monthly demand patterns ($demand_{i,t}$). In the cases where quality issues are a concern, this is expressed using the parameter $rejRate$, forcing the model to account for the extra units to be produced. This inbound flow is represented by $X_{j,i,m,z,y}$, as the sum of flows from all the origin points j that flow into locations c using any mode z.

$$\sum_{m \in M_{products}} \sum_{j \in F_{IN_{c/fp}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} \quad = \quad \sum_{t} demand_{i,t} \cdot \frac{1}{(1 - rejRate)} \qquad , \forall\, y, \forall\, (i \in L_c) \tag{4.2}$$

Manufacturing

The manufacturing stage is a critical aspect of this model due to the need of selecting the forming technologies, dictating flows both up and downstream in the supply chain.

The following equation (4.3) constrains the production ($P_{i,p,y}$) at each i, essentially by converting the whole equation to time units (hours) and limiting the production by the resources available at that entity. For this, the production level is multiplied by the time and amount of resources r needed to complete a manufacturing activity a (represented by $pTOP_{a,p}$ and $pBOT_{r,p,a}$, respectively), bounded by the available time (in hours) of the resources hired/bought ($R_{r,i,y}$). As each manufacturing activity may be carried out in batches, dividing the left hand side by $batch_{a,p}$ accounts for this aspect, and the parameter $scaleUp_{a,p}$ parametrises what should be the ratio to industrialisation for each activity if laboratory data is used as input. The parameter $prod_r$ represents the productivity, in percentage, associated with the resources, if this value is considered time-static for each resource, otherwise using a parameter $learningCurve_{r,y}$ would allow to include the learning effect and efficiency gains mentioned earlier. (Note: $p \equiv m \in M_{products}$).

$$\sum_{a} pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot \frac{1}{batch_{a,p}} \cdot scaleUp_{a,p} \cdot P_{i,p,y} \quad \leqslant prod_r \cdot R_{r,i,y} \cdot t_{h/shift} \cdot t_{shifts/d} \cdot t_{ds/mth} \cdot t_{mths/yr}$$
$$, \forall\, i, p, r, y \qquad (4.3)$$

Constraints 4.4 and 4.5 have an important role in the context of the problem, avoiding the production of simultaneous products p. As discussed earlier, the difference between products p is artificial, only representing the products being manufactured through distinct manufacturing processes. In this sense, it is possible to include in the model the forming process selection feature (Ω_p), since equation 4.5 limits this to only one type of product.

$$\sum_{y} P_{i,p,y} \leqslant bigM \cdot \Omega_p \qquad , \forall\, (i \in L_f), \forall\, p \qquad (4.4)$$

$$\sum_{p} \Omega_p = 1 \qquad (4.5)$$

Resources

As described in the previous equation, the level of resources dictates and constrains the manufacturing process all along. In this case, both labour and manufacturing technologies are considered resources since most parameters follow a similar structure in terms of cost and characterisation.

Equation 4.7 is used to maintain the balance of resources (represented by $R_{r,i,y}$) at location i, ensuring that any increase or decrease in the workforce or the technology base is properly incremented/decremented (hence the $AddR_{r,i,y}$ and $CutR_{r,i,y}$ variables) according to associated costs/impacts. The level of resources at a given period y equals the initial level ($initRes_{r,i}$) - for the first period, as in eq. 4.6 - or the previous inventory - for other periods, as in eq. 4.7 - plus the resources added, and minus the resources removed/cutted, respectively, if $r \in R_{labour}$.

$$initRes_{r,i} + AddR_{r,i,y} - CutR_{r,i,y} = R_{r,i,y} \qquad , \forall\, r, i, \forall\, \{y \in Y : y = 1\} \qquad (4.6)$$
$$R_{r,i,y-1} + AddR_{r,i,y} - CutR_{r,i,y} = R_{r,i,y} \qquad , \forall\, r, i, \forall\, \{y \in Y : y > 1\} \qquad (4.7)$$

Material Balance

Maintaining balance between inbound and outbound flows at each entity and for every period is a necessary premise in most models. The conservation of material in each entity throughout the network is essential to ensure that no material is lost.

Warehouses

Equation 4.9 ensures that the inbound flow of material ($X_{j,i,m,z,y}$) of a warehouse $i \in L_w$, for a given period, plus the inventory stored in the previous period is equal to the outbound flow of the same location i plus the inventory stored in that same period. Exception is made for the first period where stock levels are initialised ($initStock_{m,i}$), as described in eq. 4.8. The inventory (or stock level) kept at that location for material m and period y is given by $S_{i,m,y}$.

$$
\begin{aligned}
initStock_{m,i} + \sum_{j \in F_{IN_{wh/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} &= S_{i,m,y} + \sum_{j \in F_{OUT_{wh/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \\
,\forall\, m, \{y \in Y : y = 1\}, \forall\, (i \in L_w) & \qquad (4.8) \\
S_{i,m,y-1} + \sum_{j \in F_{IN_{wh/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} &= S_{i,m,y} + \sum_{j \in F_{OUT_{wh/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \\
,\forall\, m, \forall\, \{y \in Y : y > 1\}, \forall\, (i \in L_w) & \qquad (4.9)
\end{aligned}
$$

Factories

Regarding finished products in factories, equation 4.11 ensures that the outbound flow at a given period y equals the start-up inventory ($initStock_{p,i}$) - for the first period, as in eq. 4.10 - or the previous inventory - for other periods, as in eq. 4.11 - plus the quantity produced, and minus the quantity shipped. The outbound flow is represented by $X_{i,j,p,z,y}$, as the sum of flows destined to all points j out of locations i using any mode z. (Note: $p \equiv m \in M_{products}$).

$$
\begin{aligned}
initStock_{p,i} + P_{i,p,y} &= S_{i,p,y} + \sum_{j \in F_{OUT_{f/fp}}} \sum_{z \in N_{NET}} X_{i,j,p,z,y} \\
,\forall\, p, \forall\, i \in L_f, \forall\, \{y \in Y : y = 1\} & \qquad (4.10) \\
S_{i,p,y-1} + P_{i,p,y} &= S_{i,p,y} + \sum_{j \in F_{OUT_{f/fp}}} \sum_{z \in N_{NET}} X_{i,j,p,z,y} \\
,\forall\, p, \forall\, i \in L_f, \forall\, \{y \in Y : y > 1\} & \qquad (4.11)
\end{aligned}
$$

Equation 4.13 concerns the balance of raw materials in factories. This equation ensures that the inbound flow of raw materials of a factory plus the inventory at the previous period is either transformed into finished products or (more) stock is built at that same period. Exception is made for the first period where stock levels are initialised ($initStock_{m,i}$), similarly to previous balance equations and described in eq. 4.12.

The correspondence between raw materials and finished products is given by $pBOM_{m,p}$, which is nothing less than the BOM required for the product using a specific forming process. The parameter $scaleUpMult$ is used to re-scale the BOM should the laboratory data be considered as input and there is the need to establish a ratio to industrialisation.

$$
\begin{aligned}
initStock_{m,i} + \sum_{j \in F_{IN_{f/rm}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y-1} &= S_{i,m,y} \\
&+ \sum_{p} \sum_{j \in F_{OUT_{wh/fp}}} \sum_{z \in N_{NET}} pBOM_{m,p} \cdot scaleUpMult \cdot P_{i,m,y} \\
&,\forall\, (m \in M_{mat}), \forall\, (i \in L_f), \forall\, \{y \in Y : y = 1\} \qquad (4.12) \\
S_{i,m,y-1} + \sum_{j \in F_{IN_{f/rm}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y-1} &= S_{i,m,y} \\
&+ \sum_{p} \sum_{j \in F_{OUT_{wh/fp}}} \sum_{z \in N_{NET}} pBOM_{m,p} \cdot scaleUpMult \cdot P_{i,m,y} \\
&,\forall\, (m \in M_{mat}), \forall\, (i \in L_f), \forall\, \{y \in Y : y > 1\} \qquad (4.13)
\end{aligned}
$$

Equation 4.14 establishes that factories' inbound flows, using any mode z, are equal to the quantity of material ordered, where $PO_{i,j,m,y}$ represents the purchase orders which must respect a given lot size (lot_m). The inbound flows of the factories are represented by $X_{i,j,m,z,y}$, and the equation is applicable to raw materials only ($m \in M_{mat}$).

$$\sum_{z \in N_{NET}} X_{i,j,m,z,y} \quad = \quad lot_m \cdot PO_{i,j,m,y} \qquad , \forall\, (m \in M_{mat}), \forall\, i, j, y \tag{4.14}$$

Cross-docking at Airports and Seaports

Global and scattered SCs often resort to multi-mode transportation for the different flows and connections between entities. In the process, exchange of material may occur in transportation hubs and there is the need to guarantee that no inventory is kept at those locations. Equations 4.15 and 4.16 feature this example for the cases of air and maritime transportation, respectively. For each time period, all the inbound flows of airports or seaports, represented by $X_{j,i,m,z,y}$, must be equal to the respective outbound flows, represented by $X_{i,j,m,z,y}$. These equations ensure that no inventory is kept and these entities act only as material transfer or cross-docking points.

$$\sum_{j \in F_{IN_{air/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} \quad = \quad \sum_{j \in F_{OUT_{air/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \qquad , \forall\, m, \forall\, (i \in L_{air}), \forall\, y \tag{4.15}$$

$$\sum_{j \in F_{IN_{port/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} \quad = \quad \sum_{j \in F_{OUT_{port/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \qquad , \forall\, m, \forall\, (i \in L_{port}), \forall\, y \tag{4.16}$$

Storage

The storage of raw materials and/or finished products in warehouses or factories is another matter of concern in network planning. In equation 4.17 this is accounted for the raw materials, whereas in eq. 4.18 the same occur for the finished products. The biggest difference between the two is related with the units, where raw materials are limited in weight of the material and finished products are limited in product units. The symbol $cellCap_{m,i}$ is parameter for this capacity, which may vary according to the material stored, and $CellsOpen_{i,y}$ concerns the number of these cells be open at each location. Following the same rationale, it is also possible to define the capacity in area units, as described in equation 4.19. Equation 4.18 sets the value for Θ_i, meaning the facility is either open or closed.

$$\sum_{m \in M_{mat}} nomWeight_m \cdot S_{i,m,y} \leqslant cellCap_{m,i} \cdot CellsOpen_{i,y} \qquad , \forall\, [i \in (L_w \cup L_f)], \forall\, y \tag{4.17}$$

$$\sum_{m \in M_{product}} S_{i,m,y} \leqslant cellCap_{m,w} \cdot CellsOpen_{i,y} \qquad , \forall\, [i \in (L_w \cup L_f)], \forall\, y \tag{4.18}$$

$$\sum_{m} nomArea_m \cdot S_{i,m,y} \leqslant cellAreaCap_{m,i} \cdot CellsOpen_{i,y} \qquad , \forall\, [i \in (L_w \cup L_f)], \forall\, y \tag{4.19}$$

$$\sum_{i,y} CellsOpen_{i,y} \leqslant bigM \cdot \Theta_i \qquad , \forall\, [i \in (L_w \cup L_f)], \forall\, y \tag{4.20}$$

Transportation

Capacities of modes

In equations 4.21, 4.22 and 4.23, the number of trips (represented by $T_{z,i,j,y}$) is limited to maximum capacity for materials ($tCapMat_z^{max}$), maximum capacity for products ($tCapProd_z^{max}$) and minimum quantity ($tCap_z^{min}$), respectively. These are defined with respect to transportation using trucks only. The number of trips is important to derive since a significant portion of costs and impacts are usually indexed to each trip, in addition to the typical mileage/distance variable cost/impact.

$$tCapMat_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{m \in (M_{mat} \cap N_{NET})} nomWeight_m \cdot X_{i,j,m,z,y} \quad , \forall\,(z \in Z_{truck}), \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.21}$$

$$tCapProd_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{p \in N_{NET}} X_{i,j,p,z,y} \quad , \forall\,(z \in Z_{truck}), \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.22}$$

$$tCap_z^{min} \cdot T_{z,i,j,y} \leqslant \sum_{m \in N_{NET}} X_{i,j,m,z,y} \quad , \forall\,(z \in Z_{truck}), \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.23}$$

The parameter $nomWeight_m$ in equation 4.21 allows to convert each flow ($X_{i,j,m,z,y}$) into weight units seeing that the maximum capacity of the mode is also defined in weight, whereas in equation 4.22 the maximum capacity for products is defined in units of product due to volume limitations.

Equations 4.24, 4.25 and 4.26 have a purpose similar of the previous set of equations but are dedicated to air and maritime transportation.

$$tCapMat_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{m \in (M_{mat} \cap N_{NET})} nomWeight_m \cdot X_{i,j,m,z,y} \quad , \forall\,[z \in (Z_{boat} \cup Z_{plane})], \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.24}$$

$$tCapProd_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{p \in N_{NET}} X_{i,j,p,z,y} \quad , \forall\,[z \in (Z_{boat} \cup Z_{plane})], \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.25}$$

$$tCap_z^{min} \cdot T_{z,i,j,y} \leqslant \sum_{m \in N_{NET}} X_{i,j,m,z,y} \quad , \forall\,[z \in (Z_{boat} \cup Z_{plane})], \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.26}$$

Equations 4.27 and 4.28 limit the number of trips to the strict amount defined in the outsourcing contract, here materialised as $tCont_z^{max}$, the first equation being for boat or plane and the latter for road transportation.

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y} \quad , \forall\,[z \in (Z_{boat} \cup Z_{plane})], \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.27}$$

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y} \quad , \forall\,[z \in Z_{truck}], \forall\,[(i,j) \in N_{ALL}], \forall\, y \tag{4.28}$$

Fleet

An important decision on every SC network design problem is to define the appropriate mix of outsourced and in-house activities. In this model, the transportation network is open to this type of decisions, being possible to acquire trucks and own a private fleet, or outsource transportation entirely.

Regarding the fleet composition at location i, the fleet level at a given period y equals the initial fleet composition ($initFleet_{z,i}$) - for the first period, as in eq. 4.29 - or the previous fleet composition - for other periods, as in eq. 4.30 - plus the number of vehicles bought and minus the ones sold.

$$
\begin{aligned}
initFleet_{z,i} + BuyT_{z,i,y} - SellT_{z,i,y} &= F_{z,i,y} \quad , \forall\, z, i, \forall\, \{y \in Y : y = 1\} \qquad (4.29)\\
F_{z,i,y-1} + BuyT_{z,i,y} - SellT_{z,i,y} &= F_{z,i,y} \quad , \forall\, z, i, \forall\, \{y \in Y : y > 1\} \qquad (4.30)
\end{aligned}
$$

The next set of equations allow to define the number of trucks needed and should be appended to the private fleet. In equation 4.31, the number of trucks needed per period ($Tr^{period}_{z,i,y}$) is defined after the distance travelled ($= 2 \cdot dist_{i,j} \cdot T_{z,i,j,y}$) over the driving time per truck per time period ($v^{avg} \cdot driveHrsWk^{max} \cdot wkTimePeriod$). The parameter $dist_{i,j}$ is the distance between two entities, v^{avg} is the average speed and $driveHrsWk^{max}$ is the maximum number of driving hours per week. Equation 4.32 sets the value for the fleet level ($F_{z,i,y}$) to the maximum of vehicles needed in the period. Equation 4.33 mandates that the budget for investment in trucks ($invTruck^{max}$) should not be exceed and $tAcquire_z$ is the cost of acquiring one vehicle.

$$
\begin{aligned}
Tr^{period}_{z,i,y} &= \frac{\sum_{j \in N_{intra}} (2 \cdot dist_{i,j} \cdot T_{z,i,j,y})}{v^{avg} \cdot driveHrsWk^{max} \cdot wkTimePeriod} \quad , \forall\, (z \in Z_{truck}), \forall\, i, y \qquad (4.31)\\
F_{z,i,y} &\geqslant Tr^{period}_{z,i,y} \quad , \forall\, (z \in Z_{truck}), \forall\, i, y \qquad (4.32)\\
\sum_{z,i} tAcquire_z \cdot BuyT_{z,i,y} &\leqslant invTruck^{max} \quad , \forall\, y \qquad (4.33)\\
& \qquad (4.34)
\end{aligned}
$$

Physical constraints

Multi-mode transportation implies that the flows from hub to hub are made using one mode z, whereas the inbound flows of departing node and outbound flows of arriving node are made using a different mode z. Air and maritime transportation are examples of this hub-to-hub connection that need to rely on complementary modes for a full end-to-end transportation. Equations 4.35 and 4.36 are used to model this aspect for the cases of air and maritime transportation, respectively. The flows entering in the hub by modes other than plane or boat, must leave the hub by plane or boat, respectively.

$$
\begin{aligned}
\sum_{\substack{j \in N_{NET} \\ j \notin L_{air}}} \sum_{z \notin Z_{plane}} X_{j,i,m,z,y} &= \sum_{\substack{j \in N_{NET} \\ j \in L_{air}}} \sum_{z \in Z_{plane}} X_{i,j,m,z,y} \quad , \forall\, m, \forall\, (i \in L_{air}), \forall\, y \qquad (4.35)\\
\sum_{\substack{j \in N_{NET} \\ j \notin L_{port}}} \sum_{z \notin Z_{boat}} X_{j,i,m,z,y} &= \sum_{\substack{j \in N_{NET} \\ j \in L_{port}}} \sum_{z \in Z_{boat}} X_{i,j,m,z,y} \quad , \forall\, m, \forall\, (i \in L_{port}), \forall\, y \qquad (4.36)\\
& \qquad (4.37)
\end{aligned}
$$

Capacities of Entities

Equation 4.38 forces a hard constraint for supplier capacity.

$$\sum_{j} PO_{i,j,m,y} \quad \leqslant \quad supCapacity_i \cdot \varTheta_i \quad ,\forall\,(m \in M_{mat}), \forall\,(i \in L_{sup}), \forall\, y \tag{4.38}$$

Equations 4.39 and 4.40 ensure that flow in and out of entities can only exist if origin and destination entities are open ($\varTheta_i$ and $\varTheta_j$, respectively).

$$\sum_{(m,z,j)\in N_{NET}} X_{j,i,m,z,y} \quad \leqslant \quad bigM \cdot \varTheta_i \quad ,\forall\,(i \notin L_{sup}), \forall\, y \tag{4.39}$$

$$\sum_{(m,z,i)\in N_{NET}} X_{i,j,m,z,y} \quad \leqslant \quad bigM \cdot \varTheta_j \quad ,\forall\,(j \notin L_{sup}), \forall\, y \tag{4.40}$$

4.2.5 | Objective Functions

This subsection introduces the different objective functions used in the model. Additional indexes, sets and variables are described before the actual equations and parameters are referred in the descriptive text. A more compact but complete version of the proposed model is provided in Appendix A.

Economic Objective Function

Let $\varGamma$ be the set for the type of investments such as facilities, equipment and transportation assets. In this sense, $\gamma = (1, 2, \ldots, n)$ is the index to represent the different types of investment.

Auxiliary variables for the economic objective function are summarised in table 4.4. In Appendix A the objective function is presented with more detail and split in several equations to simplify in understanding the component pieces.

Table 4.4: Variables for Objective Functions

Economic Auxiliary variables:	
DC_y	Depreciation rate for period y
FCI_γ	Fixed capital investment per γ
NE_y	Net earnings in period y
CF_y	Cash flow for period y
NPV	Net present value

The economic objective function (equation 4.41) is based on the general formulation of NPV introduced earlier. The initial investments are represented by FCI_γ (in equation 4.42), where γ is the type of investment. The CF_y corresponds to incoming cash flows that are computed through equation 4.43, where NE_y represents the earnings/revenues net from variables costs and other costs such as taxes ($taxRt$) and depreciation of investments (DC_y).

Equation 4.45 includes the total costs coming from the terms of the equation. The costs of buying raw materials per period are determined in the first term, where $matP_{m,i}$ is the price of each material at different suppliers, lot_m is the lot size of material m and $PO_{i,j,m,y}$ is the quantity ordered. The costs related to labour are computed in the following term, including both variable and fixed costs related to hiring, firing and maintaining human resources in location i in period y. The third term of equation 4.45

is used to determine the variable costs associated with technologies, since investments in these technologies are already included in equation 4.42. Variable and fixed costs of transportation are described in the fourth term, where $cContract_z$ is the annual cost of signing contract with any carrier, avC_z, fp and $vhcMntc_z$ are the average fuel consumption, fuel price and vehicle maintenance, respectively, being associated with road transportation. The parameters $tripRt_z$ and $kmRt$ are the rate per trip and the variable cost per kilometre set up by the carrier. Handling costs at transportation hubs are calculated in following term, where $hubVarC_i$ is the cost of handling materials at location i, and $X_{i,j,m,z,y}$ and $X_{j,i,m,z,y}$ are the inbound and outbound flows, respectively. The costs of storing material are determined in the last term of equation 4.45, where $cellC_{m,i}$ is the cost of opening a unit of a warehouse (e.g., 1 m^2 cell) and $holdC_m$ is the cost of holding inventory per unit or weight of material stored.

$$\textit{maximise} \qquad NPV = \sum_{y} \left(\frac{CF_y}{(1 + discRt)^{(y)}} \right) - \sum_{\gamma} FCI_\gamma \tag{4.41}$$

$$FCI_\gamma = \begin{cases} \sum\limits_{i \in L_f \cup L_w} (inv_i^{facility} + inv_i^{others}) \cdot \mathit{\Theta}_i, \quad \gamma = 1 \\ \sum\limits_{p} \Big[\sum\limits_{\substack{y \\ m \\ r \in R_{tech}}} (inv_r^{equip} \cdot AddR_{r,i,y}) \\ +(inv_p^{tooling} \cdot \mathit{\Omega}_p)\Big], \quad \gamma = 2 \\ \sum\limits_{z \in Z_{fleet}} \sum\limits_{i} inv_z^{truck} \cdot BuyT_{z,i,y}, \quad \gamma = 3 \end{cases} \tag{4.42}$$

Where $\gamma = 1$ represents the facilities and related investments, $\gamma = 2$ is for the equipment and $\gamma = 3$ is for the tangible assets (trucks)

$$CF_y = \begin{cases} NE_y & , \quad t = 1, \ldots, NT - 1 \\ NE_y + \sum\limits_{\gamma} (sv_\gamma \cdot FCI_\gamma) & , \quad t = NT \end{cases} \tag{4.43}$$

NT is the last period

$$DC_y = \sum_{\gamma} DP_{\gamma,y} \cdot FCI_\gamma \tag{4.44}$$

$$\begin{aligned} NE_y = (1 - taxRt) \cdot \Bigg[& annualRevenue_y - \sum_{y} \Big[\sum_{m,i,j} (matP_{m,i} \cdot lot_m \cdot PO_{i,j,m,y}) \\ & + \sum_{\substack{i \\ r \in R_{labour}}} [(firingC_r \cdot CutR_{r,i,y} + hiringC_r \cdot AddR_{r,i,y}) + (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y})] + \\ & \sum_{\substack{i \\ r \in R_{tech}}} (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y}) + \sum_{i,j,m} (\sum_{z} (cContract_z \cdot \zeta_{z,y})) \\ & + \sum_{z \in Z_{truck}} ((\frac{avC_z}{100} \cdot fp + vhcMntc_z) \cdot 2 \cdot dist_{i,j} \cdot T_{z,i,j,y}) + \sum_{z \in Z_{plane} \cup Z_{boat}} ((tripRt_z + kmRt \cdot dist_{i,j}) \cdot T_{z,i,j,y}) \\ & + \sum_{j,i \in L_{mtp}} (hubVarC_i \cdot (X_{i,j,m,z,y} + X_{j,i,m,z,y})) + \sum_{i,m} (cellC_{m,i} \cdot CellsOpen_{i,y} + holdC_m \cdot S_{i,m,y}) \Big] \Bigg] \\ & + \Big(taxRt \cdot DC_y \Big) \end{aligned} \tag{4.45}$$

Environmental Objective Function

Let Λ be the set for the midpoint impact categories from the LCA. In this sense, $\lambda = (1, 2, \ldots, n)$ is the index to represent these categories.

The only auxiliary variable for the environmental objective function is $EnvImpact$. In Appendix A the objective function is presented with more detail and split in several equations to simplify in understanding the component pieces.

The environmental objective function (equation 4.46) is presented below, being adapted from Mota et al. (2017) and having the same goal of comparing different SC network designs rather than performing an accurate environmental characterisation of the SC.

The objective function (equation 4.46) is a 'weighted sum' of all environmental impact categories λ according to a normalisation factor ($normF_\lambda$) that is used to aggregate into a single score. Equation 4.46 includes the total impact per category λ and per period y, which includes five SC activities and respective terms: transportation, manufacturing, materials, storage and entity installation. Given that energy consumption is the largest portion of the environmental impact of manufacturing (excluding impacts associated with materials), this is used to model the impacts associated with manufacturing. The manufacturing impact in the first term of equation 4.46 is given by $envFact^{res}_{\lambda,r}$, which corresponds to GHG emissions in kg of Carbon Dioxide equivalent (CO_2e) per hour of using resource r, multiplied by the total effective production time needed ($pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot P_{i,p,y}$). The second term is used to calculate the impact associated with the total raw materials bought ($PO_{i,j,m,y}$), where $matFootprint^{supplier}_{\lambda,m,i}$ is the impact per unit of raw material m bought/consumed from supplier i. A third term describes the environmental impact of transportation given the impact per kg.km transported ($envFact^{transp}_{\lambda,z}$), where $X_{i,j,m,z,y}$ is the flow of material transported, $dist_{i,j}$ is the distance and $nomWeight_m$ is the weight per unit of material m. Similarly, two last terms determine the environmental impact of storing material, given the impact per unit of material m stored ($envFact^{storage}_{\lambda,m}$), and opening entities, given the total impact of installing facilities at location i ($envFact^{entity}_{\lambda,i}$), respectively.

$$
\begin{aligned}
&\textit{minimise} \quad EnvImpact = \sum_{\substack{\lambda \\ y}} normF_\lambda \cdot \Bigg[\sum_{\substack{p \\ a \\ i \in L_f}} (envFact^{res}_{\lambda,r} \cdot pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot P_{i,p,y}) \\
&+ \sum_{m} \sum_{(i,j)} (matFootprint^{supplier}_{\lambda,m,i} \cdot lot_m \cdot PO_{i,j,m,y}) + \sum_{\substack{z \\ (m,i,j) \in N_{NET}}} (envFact^{transp}_{\lambda,z} \cdot nomWeight_m \cdot dist_{i,j} \cdot X_{i,j,m,z,y}) \\
&+ \sum_{\substack{m \\ i \in (L_f \cup L_w)}} (envFact^{storage}_{\lambda,m} \cdot S_{i,m,y}) + \sum_{i \in (L_f \cup L_w)} (envFact^{entity}_{\lambda,i} \cdot \Theta_i) \Bigg] \qquad (4.46)
\end{aligned}
$$

Social Objective Function

Let Ψ be the set of impact categories for the social indicator. As such, $\psi = (1, 2, \ldots, n)$ is the index to represent these categories.

The only auxiliary variable for the social objective function is $SocImpact$. In Appendix A the objective function is presented with more detail.

Objective function

The social objective function (equation 4.47) outlined next is based on the environmental objective function, considering the principles are similar to those of a LCA and a single score for the social impact is used. Regardless of the model being described for several impact categories ψ, just a single category derived from the social impact assessment framework will be employed.

The main equation (4.47) results from the aggregation of all impact categories ψ according to a normalisation factor ($normF_{\psi}$) that is used (if defined) to aggregate into a single score. In equation 4.47 the total impact per category ψ and per period y is calculated, which includes five SC activities and respective terms: transportation, manufacturing, materials, storage and entity installation. The manufacturing impact in the first term is given by $socFact_{\psi,p}^{manuf}$, which corresponds to a social impact per unit of product p produced ($P_{i,p,y}$). A second term is used to calculate the impact associated with the total raw materials bought ($PO_{i,j,m,y}$), where $matSocFootprint_{\psi,m,i}^{supplier}$ is the impact per unit of raw material m bought/consumed from supplier i. The third term describes the impact of transportation given the social impact per trip using z ($socFact_{\psi,z}^{transp}$), where $T_{z,i,j,y}$ is the number of trips made. In the last two terms the social impact of storing material and opening entities are calculated, given the impact per unit of material m stored ($socFact_{\psi,m}^{storage}$) and the impact of installing facilities at location i ($socFact_{\psi,i}^{entity}$), respectively.

$$\textit{minimise} \quad SocImpact$$

$$= \sum_{\psi} \sum_{y} normF_{\psi} \cdot \Bigg[\sum_{p,a} \sum_{i \in L_f} (socFact_{\psi,p}^{manuf} \cdot P_{i,p,y}) + \sum_{m} \sum_{(i,j)} (matSocFootprint_{\psi,m,i}^{supplier} \cdot lot_m \cdot PO_{i,j,m,y})$$
$$+ \sum_{(m,i,j) \in N_{NET}} \sum_{z} (socFact_{\psi,z}^{transp} \cdot T_{z,i,j,y}) + \sum_{m} \sum_{i \in (L_f \cup L_w)} (socFact_{\psi,m}^{storage} \cdot S_{i,m,y}) + \sum_{i \in (L_f \cup L_w)} (socFact_{\psi,i}^{entity} \cdot \Theta_i) \Bigg] \tag{4.47}$$

4.3 | Summary of Chapter 4

This chapter describes the problem and provides the context for the development of the referred sustainable SC optimisation model for the aerospace industry. A model framework is presented and the three model objectives are also explained. For the economic objective is presented the general formula of the NPV, for the environmental objective is detailed the data collection process based on the LCA and a social impact framework is introduced for the social objective.

A Mixed-Integer Programming (MIP) model is proposed for aiding on decisions of global network SC design for CFRP manufacturing in aerospace industries. Several modelling assumptions are also provided along with a detailed explanation of the mathematical formulation and notation. In general, the model considers a (1) superstructure of entities and existing or potentially new geographical locations, a (2) transportation network, the (3) distance between all entities/locations, a (4) set of resources, materials, technologies, and time constraints, and respective manufacturing needs, (5) a set of alternative manufacturing processes, and the (6) costs and social and environmental impacts for all of decisions. This model is based on sustainable performance measures, thus aiming at maximising economic return, and minimising environmental and social impacts.

The chapter that follows introduces the case study and describes all the parameters to be plugged into the model just presented.

5 | Case Study

Following the chapter of problem definition and detailed explanation of the proposed model, the present chapter introduces the case study on which the model is tested.

This chapter is divided into five sections, the first being dedicated to providing context for the case study, with the presentation of the focal company and industrial partner - Embraer. The second section discusses the general assumptions and simplifications that are made to overcome difficulties in data collection. The third section presents the actual data of the case study, and the fourth section presents the data for the performance measures. Fifth and last section summarises the main contents discussed in the chapter.

5.1 | Embraer Supply Chain

The case study considered focuses on Embraer. Embraer is a major player in the segment of aircraft up to 100 seats (Regional and Executive Jets). In addition to the commercial and executive aviation segments, the defence and military-focused aviation represent an essential stake in the company's performance and operations. Spread across more than 28 locations, Embraer has a strong presence in Portugal with two plants in Évora and 65% ownership of OGMA in Alverca (Embraer, 2017*a*).

This research is interested in the segment of light commercial aviation, in which Embraer accounts for roughly 30% market share and delivered 101 aircraft of their E-series in the year of 2017. Among company's drivers for sustainability are a culture of health, safety and well-being, lower depletion of natural resources and waste, reduction of atmospheric emissions aside to economic and financial sustainability (Embraer, 2017*a*).

The industry is experiencing another period of great turmoil, with Boeing and Embraer announcing a joint venture, as of July 2018, for the development of the commercial aviation segment. This move surges after an alliance between Airbus and Bombardier has come to daylight (Leahy et al., 2018). These events may have implications for the industry and respective supply chains, but there are no immediate, short-term consequences for the overall purpose of this research.

Regarding Embraer's SC, it is relevant to note the adoption of a typical configuration of a Systems' Integrator model (Santos, 2017). As described in the previous chapter, the focal company of this research is a 'Tier 1' supplier, Embraer Portugal located in Évora, and the market is the OEM (and parent company), Embraer Brasil located in São José dos Campos.

To consider a minimal working example for this case study, and given that Embraer only employs the TA and sources from a single supplier for CFRP raw materials, the two main players in composite materials are considered - Hexcel and Cytec (part of Solvay group). These companies are the leaders in composite material manufacturing and together account for around 80% of the *prepreg* supply market (Santos, 2017).

Hence, Embraer's SC starts with the two alternative suppliers for the factory in Évora, Portugal, which in turn acts as the sole supplier of the OEM in Brazil. Figure 5.1 allows for an overview of this SC and its constituent entities.

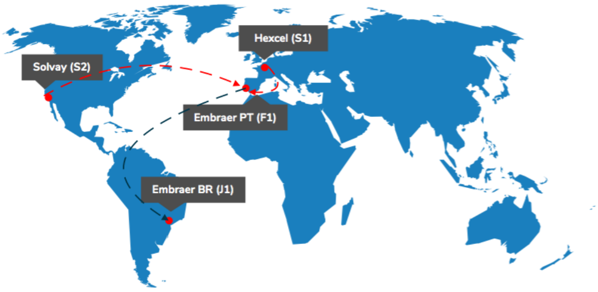

Figure 5.1: Composite materials SC of Embraer. Source: Santos (2017).

5.2 | Assumptions & Simplifications

This section presents the assumptions and simplifications made to overcome the difficulty in estimating parameters and collecting data from a real-world setting. Additional assumptions and simplifications are provided ahead whenever these are relevant for a particular parameter.

For a start, programme's lifecycle period considered is of 15 years, following the adoption of Marques (2018), and considering as a reasonable period for amortisation of investments. As mentioned earlier, given the absence of data for a real industrial setting, laboratory data for a testbed is used, and the scale-up is made according to relations provided by Marques (2018) and explained ahead.

Given the complexity of SC for laboratory-made parts is considerably lower than the equivalent counterpart, there is no information available regarding warehouses and material handling throughout the several entities. Typically, purchase of material in these cases is a one-off process, and the low volumes do not require dedicated storage facilities nor inventory keeping of any sort. Without information of alternative locations, the case study does not consider network re-design capabilities. Besides, there are no associated costs or impacts for the installation or maintenance of facilities.

Direct raw materials are the only materials considered, i.e., the fibre and resin contents that are strictly necessary to manufacture a CFRP part. However, more materials could be considered such as vacuum bags, breathers, peel plies and flow mesh, among other support materials typical of CFRP forming processes. Regarding transportation, only outsourced modes are considered since there is no information available for owning a dedicated fleet. Another critical aspect to highlight is the fact that Marques (2018) considers some shipments as Free Carrier (FCA) (e.g., RM2, RM3, and RM5), and that this is a common practice in aerospace industry. Even though, given the aim of considering transportation aspects in the model, all costs and impacts are still included in the model.

5.3 | Data Collection

Data collection is a time-consuming yet essential part of every problem-solving and research project. Quality of input data largely affects models' outputs and makes knowledge extraction and further analysis more difficult or not meaningful at all.

This section is dedicated to the presentation of the problem's data and all information collected to feed the optimisation model. Starting with the characterisation of the network, followed by a description of materials and transportation modes being used, and other general parameters are also presented.

Consider the notations for products ($P1$, $P2$, $P3$, $P4$) that represent, in truth, the same single product being manufactured using different processes (TA, VARI, VBO and TS, respectively), and are used interchangeably throughout the chapter.

5.3.1 | Network Characterisation

As described earlier, the focal entity is a factory that must select one out of four alternative forming processes and can be supplied by two other companies - Hexcel and Solvay. This factory will then supply its customer (an OEM in this case) with finished products according to a predefined demand.

The suppliers considered are the same that provide raw materials to INEGI under the IAMAT blanket project. Hence, are considered the suppliers of Embraer's SC. More recently, INEGI changed Hexcel for Chomarat for business reasons, but since locations are relatively close and materials have very similar specifications, both suppliers are considered to be the same from a network perspective.

Regarding the other entities, the factory in Évora (PT) is assumed to have a single production line which is subject to the decision of the manufacturing process to select. Ideally, there are no constraints on the capacity of this facility, and it is assumed that the production level will be equal to the demand. Concerning markets, a single point is considered, being the OEM assembly point in Brazil. The most important characteristic of this node is the demand, putting a strain on the whole supply chain to respond accordingly. In 2017*a*, Embraer delivered 101 aircraft of the commercial aviation segment, corresponding to the E-Jets previous series. Assuming the demand for aircraft will remain similar this year, the demand of wings from 'Tier 1' links would be of 202 parts. The monthly demand of 16.8 is rounded up to 17 parts per month or 204 parts per year. This assumption seems reasonable and is in line with the literature review performed that confirms the growth trend in the number of passengers, causing OEMs to increase delivery rate.

The network is summarised in table 5.1, where suppliers are represented by $i1$ and $i2$, the factory is represented by $f1$ and the only 'market' or sink point (OEM) for the flows is located in São José dos Campos (BR), represented by $j1$. In addition, transportation hubs are also considered such as airports and seaports. In table 5.1, the airports are designated by their international IATA code used by airlines and airports' entities.

Table 5.1: Entities in the case study and respective symbols

Entities	Location		Airports		Seaports	
Hexcel	Dagneux (FR)	$i1$	SNA (USA)	$airUS$	Long Beach, CA (USA)	$portUS$
Solvay	Anaheim (USA)	$i2$	LIS (PT)	$airPT$	Sines (PT)	$portPT$
Embraer	Évora (PT)	$f1$	SJK (BR)	$airBR$	São Sebastião (BR)	$portBR$
Embraer (OEM)	S.J. Campos (BR)	$j1$	LYS (FR)	$airFR$	Fos-sur-Mer (FR)	$portFR$

It is worth mentioning that not all suppliers ship all materials. In this case, Solvay only supplies the Thermoplastic Prepreg ($rm5$), while Hexcel/Chomarat provide for other raw materials. This is described next along with more characteristics of materials.

5.3.2 | Materials

There are five different raw materials, corresponding to alternative manufacturing processes, and whose quantities needed for the production of one part have to be computed according to the characteristics of the materials and manufacturers' specifications (Hexcel, 2015, 2016*a*,*b*, 2017; Solvay, 2017).

The materials used in manufacturing are presented in table 5.2, where density is in g/cm^3 and temperature is $^\circ C$. Here is assumed that lot size and thickness are intrinsic properties of the materials as well. The informations are collected from Santos (2017) and Marques (2018), based on the purchase orders from INEGI.

Table 5.2: Raw Materials

Material	Designation	Supplier	Process	Lot	Unit	Thickness	Density	Temp.
$rm1$	HexPly M21	Hexcel	TA	190	m^2	0.184 mm	1.58	-18
$rm2$	HiTape HexTow AS7	Hexcel	VARI	100	m^2	0.054 mm	1.79	-
$rm3$	HexFlow RTM6-2	Hexcel	VARI	46	kg	-	1.11	+5
$rm4$	HexPly M56	Hexcel	VBO	100	m^2	0.194 mm	1.53	-18
$rm5$	Prepreg APC-2-PEEK	Solvay	TS	13	kg	0.16 mm	1.32	-

Following the work of Santos (2017) and Marques (2018), the BOM needs to be computed according to the material properties. The goal is to implement this in the model as part of the computations prior to the optimisation, in a way that the model is prepared for future parametrisation.

In general terms, to compute the BOM per product, the area of a single layer and the total number of layers needed must be known. The number of layers can be found by dividing part's thickness by material's thickness, as in equation 5.1. So the quantity of material needed to produce one part is given multiplying part's single layer area by the number of layers and adding the waste associated with fabrication (is included in the parameter $quantityMaterial = 1 + wasteFabrication$), as in equation 5.2. In the cases where the material's unit is weight, the BOM is computed using the material's density property as shown in equation 5.3. Resin infusion process requires a given resin-to-fibre ratio to be respected, which the parameter $PercentVolume_m$ accounts for.

$$NrLayers_m = \frac{partThickness \cdot PercentVolume_m}{MatThickness_m} \tag{5.1}$$

$$PartArea_m = (partLength * partWidth) \cdot NrLayers_m \cdot quantityMaterial \tag{5.2}$$

$$PartWeight_m = materialDensity_m \cdot partVolume \cdot PercentVolume_m \cdot quantityMaterial \tag{5.3}$$

Considering a 30% waste of material, according to Snudden et al. (2014), and 60% in volume of fibre for the resin infusion (Hexcel, 2015, 2016*a*,*b*, 2017; Solvay, 2017), the resulting BOM computed manually is presented in table 5.3.

Table 5.3: Bill of Materials (BOM)

	$P1$	$P2$	$P3$	$P4$	units
$rm1$	2574	0	0	0	m^2
$rm2$	0	5265	0	0	m^2
$rm3$	0	208	0	0	kg
$rm4$	0	0	2457	0	m^2
$rm5$	0	0	0	618	kg

The BOM is a configuration of the product to be used in manufacturing, containing the quantities of each raw material. The manufacturing process is detailed next.

5.3.3 | Manufacturing

There are four alternative forming processes in manufacturing, each with different requirements in terms of resources, materials, technologies, activities and durations. These differences in manufacturing activities and resource needs are detailed below. The four forming processes are represented by the resulting products: P1 for TA, P2 for VARI, P3 for VBO and P4 for TS.

Concerning manufacturing activities, most processes include some sort of material preparation and/or tool preparation, pre-heating of both materials and tools, vacuum-bagging, curing and machining of the parts. The activities are described with detail in table 5.4, for those which information could be found. Other activities could be included/detailed such as lay-up ($a4$), applying additives ($a5$), joining multiple parts (a6), finishing, NDT/quality inspection, assembly and painting, if more information regarding time, cost and environmental impact was available. These activities are accounted for in the model, following the characterisation found in literature Baillie (2004); Gay et al. (2003); Baker et al. (2004). The complete set of activities would be as follows: tool preparation ($a1$), material preparation ($a2$), pre-heating ($a3$), lay-up ($a4$), applying additives ($a5$), vacuum-bagging ($a6$), resin infusion ($a7$), apply pressure (hot press) ($a8$), curing ($a9$), debagging/demoulding ($a10$), machining (cutting, drilling, routing, trimming, sanding) ($a11$), joining ($a12$), finishing ($a13$), NDT/quality inspection ($a14$), assembly ($a15$) and painting ($a16$). Regarding activity $a11$, it can include several internal steps such as cutting, drilling, routing, trimming and/or sanding. In terms of resource requirements, TA uses an autoclave ($o1$) and vacuum ($o4$) for the curing step, whereas both VARI and VBO demand an oven ($o2$) and vacuum ($o4$) for this cure. Thermoplastic-based TS process uses the press $o3$ to fix the shape of the part and cure it simultaneously, but still requires an oven ($o2$) for pre-heating the materials (Santos, 2017). Labour is considered a resource just like forming technologies are, and all processes require labour ($l1$) for different tasks and for different periods of time. These relations and durations are presented with more detail in the annexed tables B.2 and 5.4.

Table 5.4: Characterisation of manufacturing processes. Based on Santos (2017)

Process	Activity	Description	Time (hours)	Resources
P1 - TA	$a1$	Tool preparation	1.02	Worker
	$a2$	Material preparation		
	$a3$	Pre-heating		
	$a4$	Lay-up		
	$a6$	Vacuum-bagging		
	$a9$	Curing	5.33	Autoclave, Vacuum
	$a11$	Machining	0.17	Worker
P2 - VARI	$a1$	Tool preparation	0.88	Oven, Worker
	$a2$	Material preparation	2.33	Worker
	$a6$	Vacuum-bagging	0.83	Vacuum
	$a7$	Resin infusion	0.67	Worker
	$a9$	Curing	4.25	Oven, Vacuum
	$a11$	Machining	0.17	Worker
P3 - VBO	$a1$	Tool preparation	0.5	Oven, Worker
	$a2$	Material preparation	0.67	Worker
	$a6$	Vacuum-bagging	0.83	Vacuum
	$a9$	Curing	7.08	Oven, Vacuum
	$a11$	Machining	0.17	Worker
P4 - TS	$a1$	Tool preparation	2	Worker
	$a2$	Material preparation	2.25	
	$a3$	Pre-heating	1.08	Oven
	$a8$	Apply pressure	0.5	Press
	$a11$	Machining	0.17	Worker

All types of resources are expected to have an associated productivity/efficiency that may vary throughout time. This effect studied before is represented by a learning curve that accounts for this variation, and a rough estimate is derived from equipment efficiency studies of Bellgran and Säfsten

(2010). For machines, 95% is considered the maximum possible efficiency and 80% is the respective minimum, with a growth rate of 1.5% per year. As for workers, these are 78% and 60%, respectively, with a growth rate of 1.5%/year as well.

The number of parts produced/processed in a batch for a given activity and manufacturing process - batch size - is represented by the parameter $batch_{a,p}$. From what is known of each forming process, TA is able to cure several parts simultaneously, but this value cannot be estimated with sufficient accuracy for this nor the other processes. As such, it is assumed the value of 1 for this case study regarding the batch size in each activity for all processes.

Another important aspect of manufacturing is the scale-up that is considered from laboratory to the industrial environment. The decision of which forming process to use must be prior to the implementation of an industrial environment, demanding that laboratory data is used to infer on the industrialised process. Hence, the data used to feed the model, namely concerning activities' durations, is rescaled according to a set of ratios that enable the study of the industrial process. The scale-up in terms of costs and environmental impacts is explained ahead, yet is relevant to mention here the scale-up ratio for activities' durations. From 2 hours the process takes in a laboratory to 12 in an industrial environment, Marques (2018) derives the ratio of 6 for scaling-up the time (in hours).

Finished products that leave the factory, after the manufacturing process which transformed raw materials, have an associated weight that influences the transportation. This product weight is derived from the materials' density and nominal weight according to the quantity of material (in volume) that is used to produce that part, as detailed in annexed table B.3 (Marques, 2018). The number of finished products to be transported to the customer may differ from the quantity produced due to a given amount of parts rejected after quality inspections, even though this is considered null in the case study. The transportation aspects are discussed below, along with the particular data from the case study.

5.3.4 | Transportation

Most supply chain problems include the design of a transportation network and definition of an appropriate mix of modes to serve the different links. As referred in the previous chapter, there are three different types of transportation modes available in this case. Embraer resorts to air and maritime transportation for the long-haul connections and road vehicles for the short-haul leg between hubs and end-points. The capacity of each mode is presented in table 5.5.

Table 5.5: Capacity of transportation modes. Based on Gomes et al. (2016).

Mode	Capacity (kgs)
Truck	25,000 [1]
Large Truck	40,000 [2]
Plane	137,750 [3]
Boat	49,900,000 [4]

These capacities are standard values for general cargo transportation, even though aerospace industry is known for handling large volume parts. Sizeable products like the reference part being used

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[1] `http://www.grupotransactor.com/frota_tl.html`

[2] `http://lipasto.vtt.fi/yksikkopaastot/tavaraliikennee/tieliikennee/tavara_tiee.htm`

[3] `http://www.boeing.com.br/produtos-e-servicos/avioes-comerciais/747.page`

[4] `https://transportemaritimoglobal.files.wordpress.com/2013/11/tipologia-de-navios_antonio-costa.pdf`

(18x5m) are one example of this misfit by volume and not by weight. The transportation of finished products, in the short-haul leg, requires the use of special-sized trucks since its assumed there are no volume constraints for maritime and air transportation. It is assumed that all modes require a minimum quantity of 1 unit or 1 kg for the transport to occur.

Regarding the materials, it is important to note that not every mode can transport all materials. Attention must be paid to materials requiring cold, or high-volume products. Materials requiring cold ($rm1$, $rm3$ and $rm4$) can only be transported in refrigerated modes, whereas the finished products cannot be transported in the lower-size trucks due to the large volume.

Rail is not fit for this industry because of its roughness, potentially damaging for the sensitive materials. Despite not being used in the case study, there are several advantages in rail transportation that could offset the risks if used for less sensitive materials, namely the lower unit cost and environmental impact compared to road transportation (Heljedal, 2013; Papageorgiou and Georgiadis, 2008).

In this sense, all transportation modes and principal characteristics are summarised in annexed table B.4. In column 'Materials' the materials that a given mode is allowed to carry are described, where FP represents finished products and the numbers from one to five for the raw materials. Column 'Trips' defines the contracted maximum capacity of outsourced modes (in trips) and is a big enough value not compromise the optimal solution, following the approach from Mota et al. (2017).

It is relevant to highlight that entities are grouped in regions to account for this need of different modes of transportation. For this, three regions are considered corresponding to Europe, Brazil and the US. Transportation within these regions is considered intra-continental, and the use of trucks is recommended, whereas inter-continental transportation is only possible using plane or boat. In addition, the model allows for the possibility to include other modes of transportation or explicitly select the modes to be used, as long as it is accounted that inter-continental transportation cannot be performed by land transportation.

Another important aspect to mention when discussing transportation is the distance between each point/entity, represented by $dist_{i,j}$. The complete distance matrix can be viewed in annexed table B.9. Goetschalckx (2011) recommends the inclusion of 'adjustment factors' whenever the Euclidean distance between to points is used to account for the difference between this norm and the actual travelled path by the vehicles. However, since these distances are obtained from SeaRates.com and Google Maps, which return approximate values for each trip using the available modes, the use of an adjustment factor is not necessary.

5.4 | Objectives Data

Maintaining the same logical separation between general data and parameters from what is specific data of the performance measures, this section details the parameters for each model objective: economic, environmental and social.

5.4.1 | Economic Data

Economic metrics being the most common and well-known performance indicators helping in decision making, the quality of these decisions is affected by the input data. The parameters referred hereafter represent the costs associated with activities and elements of the supply chain, retrieved from multiple sources and several authors. There is a natural separation in cost of materials, costs associated with manufacturing (including technologies and labour) and costs of transportation. Even though additional economic parameters could be used, like the salvage value of an asset at the end of its useful life or the revenues from the sale of products, these are not available for this case study.

Hence, the sale price of finished products and total revenue are both null, resulting that the actual economic measure is the Net Present Cost (NPC) or LCC rather than the NPV. Nonetheless, it is considered a tax rate of 30% and an annual discount rate for the NPV of 9.2%, both values used by Mota et al. (2017).

The cost of raw materials to use in the case study is collected from IAMAT's order invoices, from Santos (2017) and from Marques (2018). Economic information in some of order invoices and in the work of Marques (2018) is presented in USD, so an USD/Euro (EUR) exchange rate of 0.86 is adopted. The unitary costs of raw materials to be used are summarised in table 5.6.

Table 5.6: Cost of Materials

Material	Designation	Supplier	Process	Unit	Unit Cost (€)
$rm1$	HexPly M21	Hexcel	P1 - TA	m^2	34.83
$rm2$	HiTape HexTow AS7	Hexcel	P2 - VARI	m^2	38.09
$rm3$	HexFlow RTM6-2	Hexcel	P2 - VARI	kg	71.40
$rm4$	HexPly M56	Hexcel	P3 - VBO	m^2	65.71
$rm5$	Thermoplastic Prepreg APC-2-PEEK	Solvay	P4 - TS	kg	207.39

Regarding the manufacturing process, the biggest slice of costs is that of technologies and labour. In particular, the investment in technologies represents a great deal of the total costs associated with composite manufacturing. In this case study, the costs of technologies to be used were derived by Marques (2018) based on the laboratory reference values. For the investment cost, Marques (2018) uses the price of an autoclave bought by INEGI and the price of the autoclave used by Embraer, establishing a relation between these to enable the scale-up for other technologies. This approximation is necessary since most machines are tailored according to specifications, and there is no market price for a standard version (Marques, 2018). In table 5.7 both values are presented, using a ratio of around 171.014.

Table 5.7: Cost of technologies (€). Source: Marques (2018)

	Technology	Laboratory	Scale-Up
$o1$	Autoclave	11,868	2,029,600
$o2$	Oven	2,150	367,681
$o3$	Press	5,246	897,140
$o4$	Vacuum	1,584	270,887

For the variable costs of technologies, Marques (2018) derives the hourly rate for each technology based on their power both in laboratory and industrial environments. The laboratory estimates for time and costs collected from Santos (2017) are used for the scale-up through comparison with the current process employed by Embraer. Marques (2018) assumes a ratio of 6 for scaling-up the time (in hours) - from 2 hours the process takes in laboratory to 12 in industrial environment - and a ratio of 44.44 for power (in kW) - from the 27 kW in laboratory to the equivalent 1200 kW of the industrial process. The hourly cost of workers is considered unchanged even though there may exist productivity increases due to standardisation of processes and industrialisation, but this is contemplated in the parameter of productivity.

The variable costs of technologies are summarised in table 5.8, where the power is in kW (kiloWatt), the rate is in €/h and the ratio is in kW/(€/h).

Table 5.8: Hourly rate of resources

	Resource	Power - Lab.	Power - Indust.	Rate - Lab.	Rate - Indust.	Ratio
$o1$	Autoclave	27	1,200	70	3,108	2.59
$o2$	Oven	4.8	213.3	20	889.5	4.17
$o3$	Press	3	133.3	90	3,999	30
$o4$	Vacuum	1	44.4	5	222	5
$l1$	Worker	-	-	25	25	-

Another cost factor associated with the manufacturing of composite parts is that of tooling, which is very difficult to estimate but is assumed to be a one-off acquisition with a lifetime comparable to that of the manufacturing programme. As Embraer was not able to provide this value, and being an additional factor of uncertainty, this cost is left out of the case study. Given that transportation is an important cost driver in composite materials and to consider in any SC network design problem, the different modes are described below.

Both Santos (2017) and Marques (2018) used rates for transportation between specific locations retrieved from dedicated calculators. To be used as input parameters for the model, this research is more interested in using unit costs per quantity transported through a given distance. The fixed and variables costs of transportation used are retrieved from Bianchi and Pozzi (2011) and described in table 5.9. The fare per trip is the average of fares for different destinations (sea and air) from Bianchi and Pozzi (2011), and the variable costs are adapted from Mota et al. (2017). The values for a truck are estimated based on queries to a few trucking companies in Portugal. When the transportation mode is refrigerated, the fixed and variable costs are incremented in 10%, as mentioned earlier. In the case of using a private fleet, the variable cost could be calculated using the formula $\frac{avC_z}{100} \cdot fuelPrice + vhcMntc_z$, as presented by Mota et al. (2017), but here are only considered outsourced modes since there is no sufficient data to consider a private fleet in this case study.

Table 5.9: Transportation variable costs. Source: Mota et al. (2017)

Mode	Fare per trip (€)	Variable Cost (€/km)
Truck	1000	0.3
Plane	700	0.04
Boat	188	0.01

In economics, the capital invested and/or assets owned by companies typically devalue over a given period. This depreciation rate is defined for each investment type depending on the useful lifespan considered, where facilities can devalue up to 50% in 10 years time, equipment and technologies up to 100% in 8 years and trucks up to 100% in 5 years, according to Mota et al. (2017).

5.4.2 | Environmental Data

The use of environmental performance measures is highly dependent on the ability to collect and estimate the parameters with sufficient accuracy. Otherwise, the results are not meaningful, and the effects on management and their decisions may be the exact opposite of what is needed. Here is detailed the environmental data to be used as input for the model, based on the characterisation derived from the LCA, using the same structure of discussing the impacts associated with materials, manufacturing and transportation. The boundaries for the analysis of environmental aspects encompass both manufacturing and transportation as fundamental factors of study to derive the optimal forming process.

An alternative to avoid ditching the environmental measure due to the lack of data is to use partial assessment by focusing on a smaller set of factors. The review of Eskandarpour et al. (2015) mentions the GHG emissions as the more common factor. For the sake of simplicity and following the strategy of Santos (2017), this research concentrates only on the GHG emissions, in $kg\ CO_2$e, as the measure for the environmental dimension.

Starting with the characterisation of raw materials, and according to Suzuki and Takahashi (2005), the energy intensity associated with the carbon fibres manufacturing process is 286 MJ/kg of material, whereas for the epoxy resin used in *prepregs* it is 76 MJ/kg. After conversion to kWh (1 MJ = 0.2778 kWh), producing 1 kg of carbon fibres has an energy consumption rate of 79.5 kWh and 1 kg of epoxy resin has a rate of 21.1 kWh (Santos, 2017).

Regarding the impregnation processes, Suzuki and Takahashi (2005) estimate that the production of 1 kg of *prepreg* material (common to most of forming processes) is worth 40 MJ of energy intensity, while the infusion of resin (used in VARI) presents a value varying between 10 and 13 MJ/kg. From the materials' data sheets, the fibre ratio is between 58% and 60% (Hexcel, 2015, 2016*a*,*b*, 2017; Solvay, 2017). For simplicity, the value of 60% is going to be used, since the differences are almost negligible for this matter, such that 1 kg of *prepreg* is considered to have 0.6 kg of carbon fibres and 0.4 kg of resin. Worth mentioning that the values presented are for the raw materials only, meaning *prepreg* already includes the infusion stage, but the materials needed for VARI will include this in the forming stage. For the sake of comparison among categories, the amount of energy required to produce raw materials (in kWh) is converted to $kg\ CO_2$e units, using the value 0.537 indicated by Department for Environment, Food and Rural Affairs (2008), as used by Santos (2017). From these assumptions, the values derived for the materials are presented in table 5.10. For the hourly impact of using the technological resources, Marques (2018) developed the scale-up from the power of machines used in laboratory to the equivalent available power of machines to use in the industrial environment. Based on the 27 kW of an autoclave used in laboratory, as collected by Santos (2017), to the equivalent 1200 kW of the industrial process, the ratio of 44.44 is derived (Marques, 2018). Applying this same rationale to all machines and converting to the GHG equivalent (using the factor of 0.537 mentioned before), the

Table 5.10: Materials footprint. Based on Santos (2017) and Marques (2018).

	Materials	Infusion	Total impact
$rm1$	Fibres (0.6 kg): 47.67 kWh Resin (0.4 kg): 8.45 kWh	Prepreg (1 kg): 11.11 kWh	Energy: 67.23 kWh GHG: 36.10 $kg\ CO_2$e
$rm2$	Fibres (0.6 kg): 47.67 kWh	Infusion (0.6 kg): 2.17 kWh	Energy: 49.84 kWh GHG: 26.76 $kg\ CO_2$e
$rm3$	Resin (0.4 kg): 8.45 kWh	Infusion (0.4 kg): 1.44 kWh	Energy: 9.89 kWh GHG: 5.31 $kg\ CO_2$e
$rm4$	Fibres (0.6 kg): 47.67 kWh Resin (0.4 kg): 8.45 kWh	Prepreg (1 kg): 11.11 kWh	Energy: 67.23 kWh GHG: 36.10 $kg\ CO_2$e
$rm5$	Fibres (0.6 kg): 47.67 kWh Resin (0.4 kg): 8.45 kWh	Prepreg (1 kg): 11.11 kWh	Energy: 67.23 kWh GHG: 36.10 $kg\ CO_2$e

environmental impact for each technology is summarised in table 5.11.

Table 5.11: Technologies footprint. Based on Marques (2018).

Material	Description	Power (kW)	GHG ($kg\ CO_2$e)
$o1$	1 hour using Autoclave	1200.0	644.40
$o2$	1 hour using Oven	213.3	114.54
$o3$	1 hour using Press	133.3	71.58
$o4$	1 hour using Vacuum	44.4	23.84

Transportation is another great factor of the total environmental impact of supply chains. Following the approach of Santos (2017) and Marques (2018), the database of SimaPro 8.3.0.0 is used to estimate the unit environmental impacts for each transportation mode (PRé, 2018). This environmental data is complemented with several other figures from LIPASTO (2017), a calculation system for traffic exhaust emissions and energy use in Finland by VTT Technical Research Centre of Finland Ltd.

Considering that not every parameter is available on the databases, some assumptions are necessary. It is assumed that fuel required for refrigerated trucks ($\sim$-18° C) is higher than that of just chilled trucks ($\sim$+5° C) or those without refrigeration. Even though it is very difficult to establish a fixed ratio between refrigerated and non-refrigerated transport, especially across multi-modal options, some authors estimate to be 10 to 33% increase in CO_2 emissions (Stellingwerf et al., 2018; Worall et al., 2011; Fitzgerald et al., 2011). Assuming that are neglected all differences between materials/industries, controlled environments of the experiments and between each mode, the value of 10% is used in the baseline case.

The tables with the unit environmental impact for each transportation mode is presented in annexed tables B.5, B.6 and B.7.

5.4.3 | Social Data

Based on the framework described in the previous chapter, here is presented the social characterisation for the actual case study. It must be stressed that the boundaries for the analysis of social aspects encompass the manufacturing phase as the main driver for the distinction between forming processes.

Just like for the previous objective functions, the data can be divided into materials, manufacturing and transportation, though with further simplification of the parameters that is due to poorer characterisation on social aspects. The characterisation for the manufacturing stage on social aspects does not include values for utilisation of resources, focusing on using the aggregate indicator derived earlier for the process as a whole. To allow for model's implementation and subsequent test in the light of the case study, the social impact of materials bought at suppliers and of transportation mode is arbitrarily defined, as synthesised in annexed table B.1.

Using this parameter will penalise choices not consistent with the overall quantity purchased and total distance ran, without deviating from the focal point of the manufacturing process. Since production of carbon fibres can expose workers to temperatures around 2000° C, the social impact for resins should be lower than the others that include carbon (Brigante, 2014).

All issues regarding transportation and storage are disregarded as they are assumed equal for all forming processes. Even though, for implementation and testing reasons, some values need to be assigned to materials and transportation modes. These values arbitrarily defined can be consulted in annexed table B.8.

Table 5.12 presents the social characterisation of each process, where negative impacts are assigned '+1', '0' represents neutral impact and '-1' is assigned to when positive social impacts are due.

Table 5.12: Social impact categories

	Categories	P1	P2	P3	P4
1	Exposure to heat	0	0	0	+1
2	Exposure to cold	+1	+1	+1	0
3	Exposure to micro/small particles/fibres	0	+1	0	0
4	Exp./inhalation of hazardous/toxic gases	+1	+1	0	0
5	Exposure to noise	+1	0	0	+1
6	Exposure to high-pressure environment	+1	0	0	0
7	Exposure to mechanic hazards/heavy-machinery	+1	0	0	+1
8	Long-period standing	0	+1	0	0
9	Handling movements	0	+1	0	0
10	Exposure to hazardous/toxic materials	+1	+1	0	0
11	Man-hours per part (labour-intensive)	0	+1	+1	0
12	Additional finishing	0	+1	+1	0
13	Rework, waste disposal	0	0	0	-1
Total		6	9	3	2

The generic steps of all forming processes for composite structures were described in previous chapters: impregnation, lay-up, consolidation and solidification (Mazumdar, 2002; Gay et al., 2003). Each process being different from the others, there are characteristics and activities that are responsible for this distinction. As to justify the social impacts assigned to each process, the characterisation is detailed next.

Regarding exposure to heat (1), the process with the highest peak temperature (around 390° C) is P4, and the other processes have similar cure temperatures (around 180° C), according to Santos (2017) and manufacturers' material sheets. In terms of exposure to cold (2), only the thermoplastic (P4) does not require refrigerated storage and transportation of materials.

P2 is the sole process with local resin infusion instead of using *prepregs*, thus the workers may be exposed to particles and fibres (3) from the dry plies. The same reason applies to exposure or risk of inhalation of hazardous/toxic gases (4) for P2 with the fumes and vapours of resins. P1 is also assigned '+1' on category 4 and category 10 due to the nitrogen and other toxic gases fillings and the need for the worker to physically handle these materials (González et al., 2017; US-OSHA, 2011).

In category 5 - 'Exposure to Noise', P1 has negative impact due to the noisy autoclave fillings and mechanic operation on each cycle, and P4 also requires the operation of a large-sized hydraulic press. For the same reasons, P1 and P4 have negative impact on category 7 due to workers' exposure and handling of heavy-machinery and potential risk for work accidents. The P1 is the only to be assigned '+1' on exposure to a high-pressure environment (6) due to the whole autoclave being under pressure, whereas on other processes the pressure/vacuum is applied locally to the material (Gay et al., 2003).

The process of resin infusion requires real-time feedback when applying the resin to the dry fibres to avoid dry-spot formation, which is better performed by skilled workers. For being a manual and labour-intensive task this process is difficult and expensive to be automated and industrialised in large scale (González et al., 2017), explaining the negative impact on category 8. There is also the risk of exposure and of contact with potentially irritating and dangerous materials when handling the resin and other additives, thus P2 is considered to have a negative impact on category 10 as well (US-OSHA, 2011).

In terms of handling (9), resin infusion also requires a more significant number of movements for the fact that two raw materials need to be handled for every task/activity.

For category 11, processes P2 and P3 have higher duration (with 9.1h and 9.3h, respectively) than the others (P1 takes 6.5h and P4 takes 6h), thus being assigned negative impact on both.

Processes based on open-mould (P2 and P3) forming require additional finishing (12) of the surfaces on the opposite side of the mould, which constitutes a negative impact because of the additional work involved and for the exposure to dust from trimming and sanding (US-OSHA, 2011).

The only process using thermoplastic material has positive impact due to the possibility of reheating and reforming the material, thus reducing the rework of producing a whole new part and the amount of waste being generated.

Despite the fact that thermoplastic resins are considered harmless, and no irritations or health problems have been reported, this is not sufficient to entirely exempt the technology from toxic risks. Thus, P4 is assigned a neutral impact on categories 4 and 10 rather than positive due to the existence of concerns about the presence of monomers (US-OSHA, 2011).

5.5 | Summary of Chapter 5

This chapter essentially provides an instance for model's testing based on the Embraer's SC. Necessary underlying assumptions and simplifications are provided, and several summary tables are presented with case study's data.

The case of Embraer is presented as the company is interested in studying OoA technologies for CFRP-made aerostructures and verifying its impact on their existing SC. Essentially, laboratory data is provided, and the scale-up relations necessary to adapt towards an industrial setting are described.

All information collected to feed the optimisation model is presented in this chapter and summarised in tables. Starting with the characterisation of the network, followed by a description of materials and transportation modes being used, and other general parameters are also presented. Specific data for use by the objective functions is also provided and summarised, with a more complete characterisation for the economic measures.

The next chapter presents the results from application of the proposed model to working example just presented and provides a general discussion and several recommendations.

6 | Case Study Results and Discussion

This chapter details the computational experiments and discusses the main results and findings of this research, through the implementation of an optimisation model.

The chapter includes two main sections, starting by a first section (6.1) where the workflow and set of experiments to be carried out are described, followed by a validation of the model and sensitivity analysis for the economic objective. A second section (6.2) presents the actual results for each objective function, ending with a general discussion and relevant recommendations. Given the following chapter presents the conclusions of all work developed, this chapter is exempted from a summary being this fulfilled by the general discussion.

6.1 | Model Validation and Application

To assess the model proposed, multiple numerical experiments are performed based on data from the case study. These aim at finding the optimal CFRP forming process concerning the sustainability performance measures.

The model is implemented in GAMS, a commonly used system in academia for modelling and solving mixed-integer optimisation problems. Every experiment is carried out on GAMS-IDE v24.9.1 (r63795 WIN-VS8 x86 32bit/MS Windows) running on a OSX v10.11.6 machine equipped with a 1.8 GHz Intel Core i7 processor and 4 GB of RAM (1333 MHz DDR3).

Unless indicated otherwise, all computational experiments use the input data specified in chapter 5, hereafter referred to as the baseline case.

As recommended by the industrial and research partners - Embraer and INEGI -,TS is studied solely on a separate experiment as a hypothetical alternative given the process is not technologically viable for large parts, let alone a complete wing-like reference aerostructure.

The first series of experiments start from the baseline case so the results can be compared against the work of Santos (2017) and Marques (2018) for preliminary validation of the model. This validation is based solely on the economic objective, and the unit cost for one part using each forming process is computed. The second round of preliminary experiments is carried out for assessing the sensitivity of the economic optimal solution to variations of -10% and +10% in several parameters. All parameters are kept according to baseline description except for the one being tested for impact. Then follow the experiments to determine economic performance for each forming process and find the optimal forming process for the economic objective. An additional experiment is dedicated to comparing TS economic performance against other processes. Another series of experiments on the economic objective follow to assess the impact on the economic objective of several key factors that are subject to uncertainty, namely the (1) scale-up relation between time of process in laboratory and industrial process, (2) demand, (3) batch size and (4) part length. Then, computational experiments dedicated to comparing forming processes on the environmental objective are designed to find and characterise the environmental optimal solution.

Finally, the experiments to determine social performance for each forming process and find the optimal process for the social objective.

6.1.1 | Model Validation

Models are handy to understand complex systems and should be a virtual, controllable representation of a real-world problem. Given the compromise required between model realism and model solvability, validation the model prior to initiating other analyses is critical to ensure that the results are relatively reliable and to establish terms of comparison (Goetschalckx, 2011). In the impossibility of doing this validation against real situations of industrial use, as Embraer only employs TA, results from previous research are used for this.

Hence, the work of Santos (2017) and Marques (2018) for the same forming processes is used to validate the model. The values presented by Santos (2017) correspond to a single testbed, whose dimensions were presented earlier. To validate the model, the unit cost for a single testbed is multiplied by the scale-up relation (in area) - 1200 - to obtain the value for the equivalent reference aerostructure. As for results from Marques (2018), these already take into account the aerostructure with the same dimensions and only the base scenarios are considered (2.1.1, 2.2.1, 2.3.1, 2.4.1).

Figure 6.1 shows unit costs obtained are analogous to those from Marques (2018), as opposed to results obtained by Santos (2017). This is easily explained by the adoption of most of the assumptions and principles used by Marques (2018) for the scale-up process and given that values from Santos (2017) are actually for a testbed and not for a similar-sized aerostructure. Nevertheless, unit costs obtained from both authors allow to gauge the behaviour of the model and set reference values. This previous research and findings are used ahead for comparison of results.

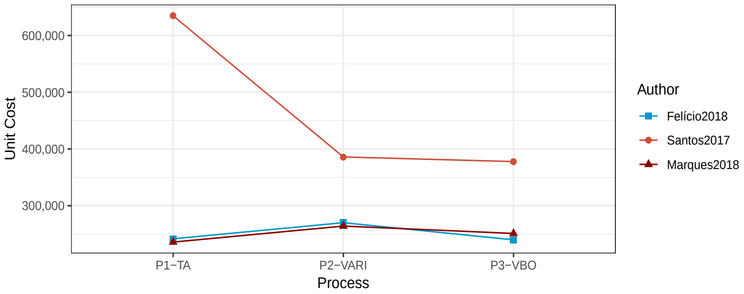

Figure 6.1: Comparison of unit cost.

6.1.2 | Sensitivity Analysis

A preliminary sensitivity analysis is carried out to better understand how parameters likely to suffer variation would impact the model. Part length, material price, material thickness, amount of waste, cost of equipment (investment costs) and transportation variable costs are examples of these parameters. These are selected according to their relevance elicited by the industrial and research partners after site visits and on data available from the case study.

Figure 6.2 depicts the results of sensitivity analysis, in percentage of deviation from the optimal Net Present Cost (NPC) when variations of -10% and +10% on input parameters are applied.

Results show that part length and raw materials' price are the parameters whose variation has a bigger effect on the NPC, closely followed by material thickness. Part length and material thickness influence the quantity of material that is needed for each part, thus increasing the total amount to be purchased from suppliers to produce the same units. Materials' price also has a considerable impact since is multiplied by each unit of material bought, naturally affecting the NPC. Surprisingly, and despite using a relatively high value of 30% waste, variations in fabrication material waste do not appear to have such a negative effect on economic performance. Although, further analysis regarding waste effect would be required since the actual range of the input parameter was from 27% to 33%.

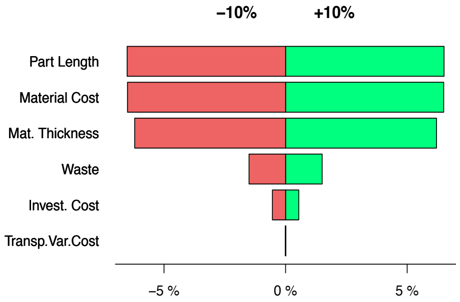

Figure 6.2: Variation in the economic objective function with each parameter.

Regarding the investment costs, considering the variation is for the optimal process, VBO, these are not considerably high and do not have such relative impact on NPC. Variable costs of transportation also do not appear to have a great impact on NPC for the optimal process, VBO. Although, more thorough sensitivity analysis could be carried out for these and other parameters.

Having studied sensitivity on a few parameters of interest, the main observation is that those parameters related to the quantity of material and material cost have more impact on NPC than other parameters. Even though, this preliminary analysis is limited to understanding the impact of NPC, more deep analyses are carried out ahead for the economic objective.

6.2 | Case Study Results

Here are presented the results in three different parts maintaining the structure adopted so far, one part for each objective. First, the results for economic objective function are revealed and interpreted in the light of the problem. Then proceed to analyses of results from both environmental and social objectives. This is followed by a general discussion of results and implications for the problem.

6.2.1 | Economic Objective

This subsection exhibits the results from economic evaluation performed as part of one of the objective functions, starting with the description of the optimal solution for the baseline case introduced in the previous chapter, followed by several analyses on key impacting parameters. The economic objective function serves as the testing template for multiple analyses that enable extrapolation for broader conclusions, given that is the most well-known and more meaningful performance measure.

Considering the baseline case presented in previous chapter, figure 6.3 and table 6.1 show the results on the economic objective function for each forming process, where the lowest value for the NPC is a better and more economical solution. Recall that NPC is symmetric to NPV due to the absence of values for annual revenue, where the goal to maximise NPV corresponds to minimisation of NPC. Hence, NPC is adopted to allow for a more clear interpretation of results. Based on the assumptions and input parameters previously discussed, the optimal process in terms of the economic objective

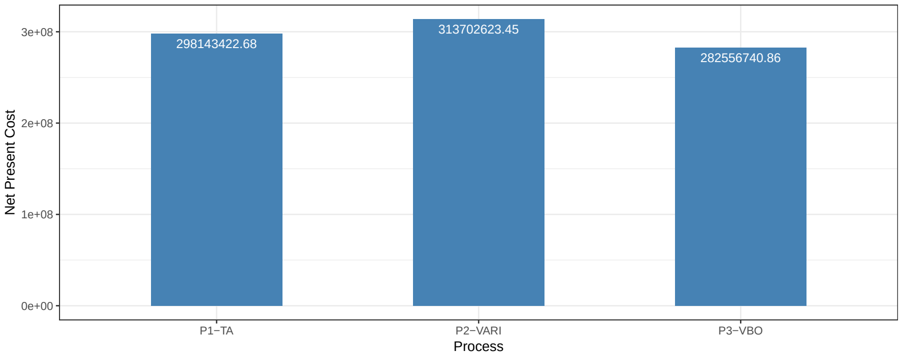

Figure 6.3: Net Present Cost (NPC) for each process (€).

function is VBO. This optimal solution implies the purchase of around 150,369 lots of OoA prepreg ($rm4$) from Hexcel/Chomarat ($i1$) located near Lyon, France. Besides, to satisfy the annual demand of 204 parts the factory located in Évora, Portugal needs to acquire six ovens and six vacuum machines and have two dedicated workers for the manufacturing process. The transportation network is composed of outsourced special-sized trucks, both with and without refrigeration, and ships for the inter-continental haul. As expected, the flow of raw materials from France to Portugal requires the use of refrigerated trucks, whereas the flow from the factory to the OEM is done by ship with the connections from seaports to end-points being done by special-sized trucks. These results can be explained essentially by the lower investment costs VBO demands when comparing with TA. Even though VARI and VBO have similar investment costs, as both use the same technologies, VBO requires less raw materials for producing the same part and the costs with labour are lower than those for VARI.

In general, the overall difference between all forming processes is not substantial. The NPC for TA is only 6% higher than the optimal process and for VARI is only 11% more than VBO. Seeing this, the optimal process for the economic objective could easily change under different assumptions and for other input parameters, hence demanding a deeper analysis on several impacting factors.

Table 6.1: Economic Results

			P1 - TA	P2 - VARI	P3 - VBO
	NPV		-298,143,423	-313,702,623	-282,556,741
Manufacturing	Production level		204	204	204
	Material Order		82,910 (RM1)	805,545 (RM2) 27,645 (RM3)	150,369 (RM4)
Resources	Tech.	Oven:	4	4	6
		Vacuum:	4	4	6
	Workforce		1	3	2

For the optimal process, VBO, the NPC yearly evolution is presented in annexed figure C.1. It is clear that investment costs are allocated to the first year and in subsequent periods the NPC is slowly decreasing at the discount rate described earlier. This analysis of NPV would be more meaningful with the inclusion of a sale price, in order to find the NPV with an actual value for the revenue. Additional analyses could be carried out for other discount and tax rates, but these are left out of this research.

In figure 6.4 is shown the new optimal solution if TS is included in the problem. Even though the unit cost of raw materials is higher, the substantially lower quantity needed to produce P4 and the lower costs of technologies makes TS the optimal forming process in this case. As suggested

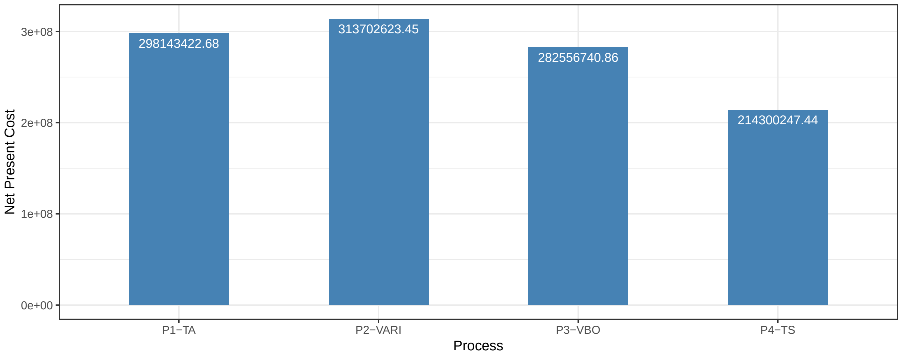

Figure 6.4: Net Present Cost (NPC) for each process, including TS (€).

before, thermal forming techniques are highly limited in terms of geometries and not yet available for large parts (Land et al., 2015). When looking for manufacturers of machines and tooling, it was only possible to find equipment capable of processing parts as large as 3x4m (Ray Products Company Inc., 2017; Industrial Custom Products Inc., 2017; Productive Plastics Inc., 2018). Hence, TS is excluded from further analyses due to the technical constraints, even though it could be considered the optimal process for smaller parts, as reported by Santos (2017), but before being a possibility in industrial setting more research and technology developments on the process are required.

Having discussed the results for economic objective, more comprehensive analyses impose to better understand the influence of different assumptions and parameters in the overall economic performance. Key factors subject to uncertainty or that have been assumed include the (1) scale-up relation between process in laboratory and industrial process, (2) demand, (3) batch size and (4) part length.

Figure 6.5 shows the effect on NPC of varying the time scale-up parameter that is used in the model. Even though the variations of the parameter only include integer values - where value 1 means the total process time in industrial environment equals that of the laboratory -, some conclusions can still be drawn regarding its influence in terms of NPC. It is worth mention that other factors have influence in these results such as batch size, which limits the number of parts that can be produced at the same time, thus implying that when the time of process increases more resources need to be added. Scale-up relations and their effect on NPC, and consequently on the optimal forming process, are among the most important features to be studied when selecting the forming process *a priori*. Successive

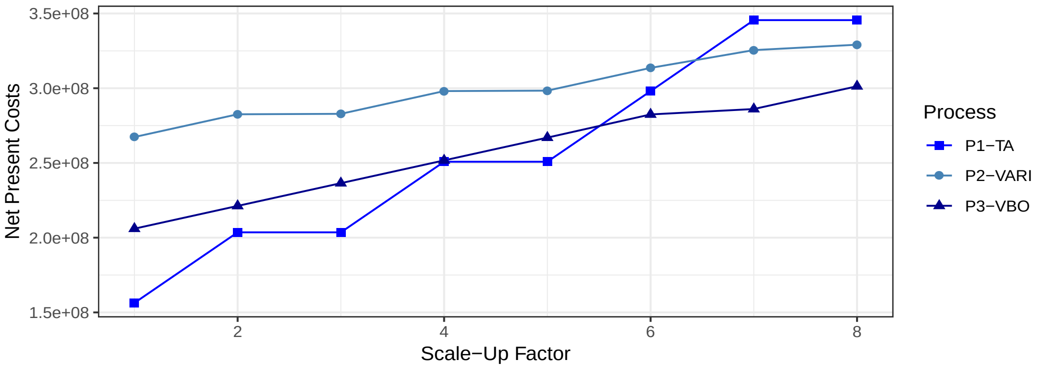

Figure 6.5: Evolution of NPC with variation of time scale-up factor.

increases in production resources for almost every value of the parameter make VARI and VBO present identical linear evolution, as opposed to TA that resembles more a step function and for which investment costs in technologies are higher. The process time of around 9 hours for both VARI and VBO and the relatively low investment costs for increases in resources (oven and vacuum machines are common to both processes) also explain this comparable behaviour. In annexed table C.1, the different decisions regarding resources can be consulted, whereas other cost factors, like material and transportation, remain unchanged across all processes. Marques (2018) uses the value of 6 for this ratio, and it can be seen that VBO is the optimal forming process if the ratio takes this value or higher. The autoclave-based process is the optimal process for values lower than 6, which is representative of why this process is the most common in aerospace industry.

It could be found that a ratio between 2 and 3 would be closer to the actual ratio, after looking into material's data sheets and focusing on total curing cycle times instead of the curing time alone. From the material's data sheet, and for "Typical Autoclave Cure Monolithic Part <15mm-48mm (0.6-1.89") thick (1)", the longest cure cycle would take 11.25 hours to complete the cycle (Hexcel, 2016*a*), and from Santos (2017) the total cure cycle time is 5.33 hours. This results in an estimated ratio of 2.11 if the lowest rates for temperature increase and decrease and longest curing time are considered. More values for this parameter could be tested, but the maximum level of 8 times is satisfactory to comprehend the underlying relations and more than that is not reasonable for industry standards, e.g., a complete cycle time taking more than 72 hours for VARI or 48 for the TA is not feasible.

In addition to studying the effect of different scale-up relations, model's behaviour under diverse ramp-up pressures is another aspect to consider in the forming technology decision process. Hence, analysing the effect of demand variation on NPC is useful to learn more about each forming process.

The fluctuation in unit cost of a reference aerostructure when demand from the OEM changes is shown in Fig. 6.6. Using unit costs makes it easier to observe the behaviour for different production scales. As mentioned earlier, production level equals demand at all times and is assumed that demand is always fully met by the factory. The general trend towards unit cost reduction is observed, despite the complex relations between different cost factors. In this case, almost all cost factors need to respond to variations in demand, where an increase in demand dictates the purchase of more raw materials, a higher number of trips is required and, most likely, the addition of more resources. Acquisition of technologies and increase in resources is needed in most cases where production capacity needs to increase. Figure 6.6 shows several steep variations in unit cost for different production/demand levels,

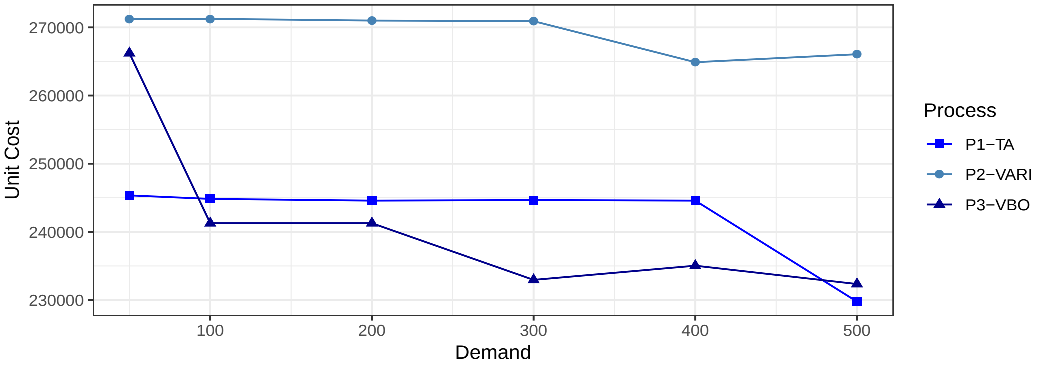

Figure 6.6: Unit cost when varying the demand.

yet most of these can be explained by shifts in the production configuration. In this case, the behaviour of VARI stands apart from that of TA and VBO, showing that the unit cost is always higher independently from demand and the increase in total costs is nearly linear. This is explained by the higher number of trips required for that process and greater costs of both transportation and materials associated with the higher quantity of raw materials. Although, VARI is the process with the largest potential to benefit from process automation, especially in the lay-up stage, as this is the most labour-intensive process of all. Another aspect to bear in mind is the batch size considered in the model, taking value 1 by default, which largely influences the results and acts as a major constraint to production ramp-ups. As mentioned before, the alternative forming processes can have different batch sizes in every manufacturing activity. However, these real values could not be estimated, thus limiting a more thorough analysis of demand variations. Nevertheless, a separate analysis is performed on the batch size parameter alone.

Seeing that the batch size is such a limiting factor for the manufacturing process, different values are tried to assess its effect on NPC. In this analysis, the same batch size is common to all activities of each process. In fact, this would not hold for a real case where each activity has different production rates and pieces of equipment have distinct capacities from each other. Results are shown in Fig. 6.7 and it is possible to learn that TA is now the optimal process for every batch size greater than one. Predictably, the greater the batch size the lower the NPC for all forming processes. After a given value, increasing batch size no longer represents an improvement since equipment and process capacity are no longer the bottlenecks. Note the impact of batch size on NPC is lower than 15% for VARI, whereas for TA this could represent up to 48% reduction in NPC and up to 27% for VBO. Investment costs in technologies define the behaviour of curves presented in Fig. 6.7, as these machines act as bottleneck in composite manufacturing due to relatively long cure cycles. Hence, if more parts can be cured at the same time, less resources are needed and manufacturing costs can be reduced substantially.

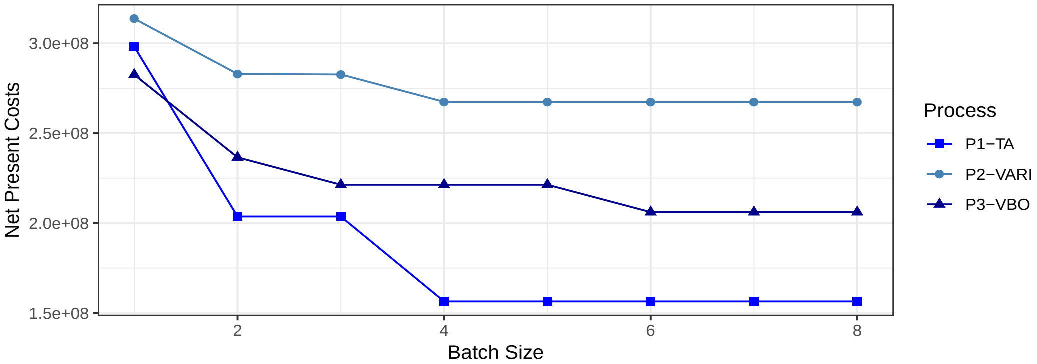

Figure 6.7: Evolution of NPC with variation of batch size.

As shown previously in the general sensitivity analysis, part size also plays an important role in global manufacturing and transportation costs. This effect is depicted in Fig. 6.8, where part length is varied from 10 to 20 meters and respective NPC is shown, assuming there are no size limitations throughout the process. These values would rapidly change if different batch sizes were considered, yet this particular analysis is relevant to the problem nevertheless.

From this figure alone, VBO appears to be the optimal forming process for all part lengths tested.

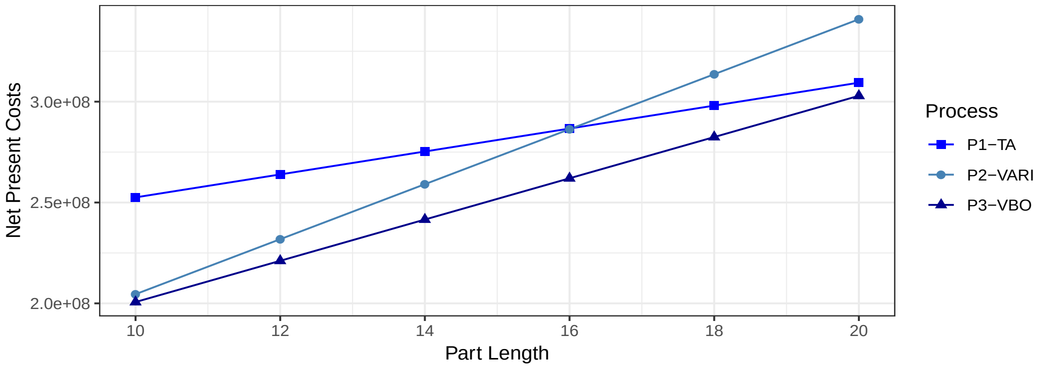

Figure 6.8: Evolution of NPC with variation of part length.

As expected, the greater the size of parts the higher the NPC, even though the slope is greater for VARI and lower for TA. Overall, NPC for TA appears to be more stable regardless of part size (for the ones considered) and, if needed, VARI should be used for smaller rather than bigger parts. Taking into account the case study is dedicated to aerospace industry and the reference aerostructure is assumed to resemble an aircraft wing, parts larger than 20 meters would constitute an interesting further study. Yet parts lower than 10 meters are not considered relevant and multiple adequate forming processes can already be found in automotive industry (Mazumdar, 2002; Brigante, 2014).

6.2.2 | Environmental Objective

Here are discussed the results for the baseline case when minimising the environmental objective function. Total environmental impact in terms of GHG emissions for each forming process is presented, in $kg\ CO_2$e, and the optimal solution is characterised.

Figure 6.9 and table 6.2 show the results on the environmental objective. Unsurprisingly, TA presents the worst performance mostly due to the use of energy-intensive autoclave curing, whereas both VARI and VBO resort to an oven with much lower impact. The process with the optimal performance is VARI, being the process with the lowest impact per unit of raw materials. Given the environmental impact for resin infusion is lower than that of producing *prepreg*, not even the greater quantities of raw material needed for VARI and which have to be transported are sufficient to offset the benefits.

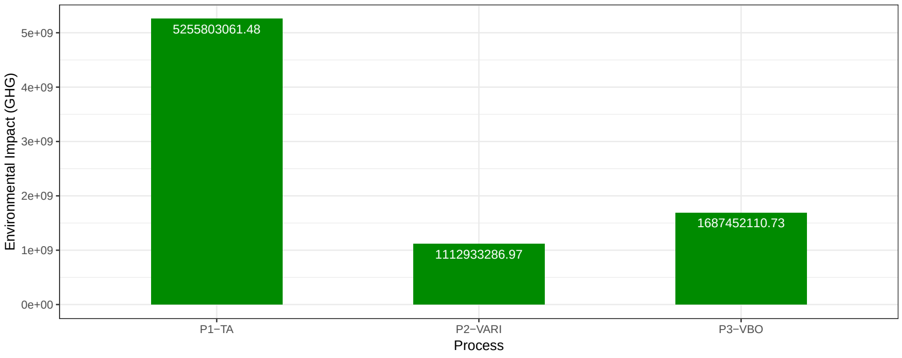

Figure 6.9: Environmental impact for each process ($kg\ CO_2$e).

This optimal solution implies the purchase of around 805,545 rolls of carbon fibre plies ($rm2$) and 27,645 lots of resin ($rm3$) from Hexcel/Chomarat ($i1$) located near Lyon, France. For this objective, the factory only needs to acquire four ovens and four vacuum machines and have one more dedicated worker to produce the same amount of P2 when compared to the economic optimum. Transportation modes selected are special-sized trucks (both with and without refrigeration), and ships for the inter-continental haul, even though transportation costs are higher than for the economic objective. Similar to the economic optimum, the flow of raw materials from France to Portugal requires the use of refrigerated trucks, whereas the flow from the factory to the OEM is done by ship with the connections from seaports to end-points being done by special-sized trucks.

Table 6.2: Environmental Results

			P1 - TA	P2 - VARI	P3 - VBO
	Env. Impact		5,255,803,061	1,112,933,287	1,687,452,111
Manufacturing	Production level		204	204	204
	Material Order		82,910 (RM1)	805,545 (RM2) 27,645 (RM3)	150,369 (RM4)
Resources	Tech.	Oven:	4	4	6
		Vacuum:	4	4	6
	Workforce		1	3	2

Environmental results obtained are similar to those from Santos (2017), where VARI is the most environment-friendly process (if TS is not considered) but closely followed by VBO with around 50% more impact. On the other hand, the environmental impact for TA is only around the double of VARI, wherein this research TA has almost four times the impact of the optimal process. Vacuum-Assisted Resin Infusion (VARI) also turns out as the best forming process in terms of environmental performance according to the complete LCA carried out by Marques (2018).

The model of eco-costs is used for the economic valuation of GHG emissions, converting the environmental impact, in $kg\ CO_2$e, to an economic penalty, in € (TU Delft, 2012). Using the value of 0.116€ per $kg\ CO_2$e, the economic penalty associated with the optimal process is equivalent to 129,100,261€. Thus, values for environmental impact appear to be overestimated and would require a more detailed analysis.

6.2.3 | Social Objective

The results of minimising the social objective function for the baseline case are presented here. Social impacts are considered adimensional but can also be referred to in points according to assignments in the assessment framework. The total social objective value for each forming process is presented in Fig. 6.10, even though it is no surprise that VBO appears as the optimal process in terms of social impact of the supply chain. Naturally, and given the simplicity and aggregation of the social objective function, the results are highly dependent on the social scores assigned earlier to each forming process. The optimal process is VBO to which was initially assigned the score of 3 points, based on the framework presented, followed by TA with a score of 6 and VARI with 9, being these multiplied by the total quantity produced. As for transportation and technology social impacts, results are almost negligible given the very small values that were arbitrarily assigned to penalise and avoid meaningless model decisions.

According to the framework presented, VBO is the process with a neutral performance on most of the harmful social categories. This social impact could be reduced with the support of automation technologies that could reduce the number of labour-intensive tasks or with improvements to the forming

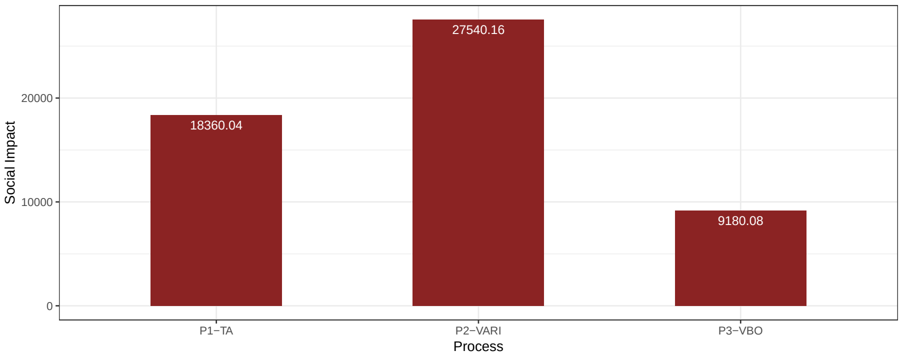

Figure 6.10: Social impact for each process (€).

process that could help prevent the rough finishing of the part after curing. On the other hand, VARI is presented as the most harmful process for workers' safety and occupational health. The positive scores on several social categories suggest the process is not prepared for industrialisation. Essentially, the fact that VARI requires two materials, implying more handling and carrying, and workers are physically exposed to the materials is affecting the social performance of the forming process.

This same naïve approach could be applied to transportation modes, extending the analysis to other important social impact factors and substantially enriching the social objective. Social impact assessment and scores could be more robust with a thorough characterisation based on surveys to industry players. Nevertheless, this preliminary version of a social impact estimator dedicated to CFRP manufacturing for the aerospace industry can be seen as a first step to include occupational health and workers safety concerns on supply chain optimisation models.

6.2.4 | General Discussion and Recommendations

Seeing the results from analysis of each objective, general considerations can be drafted regarding the optimal solutions obtained. In table 6.3 are summarised the optimal solutions (*) and decisions for each objective. For the economic and social objectives, VBO is the optimal forming process, whereas VARI is the process to operate when aiming to minimise environmental impact. These are contrasting objectives given that the process with the best environmental performance is the most expensive solution

Table 6.3: Results

		Optimising:	**Economic**	**Environmental**	**Social**
		Optimal Process	P3 - VBO	P2 - VARI	P3 - VBO
Obj. function		ECO (€)	-282,556,741 *	-313,702,623	-287,024,152
		ENV	1,687,452,111	1,112,933,287 *	1,687,453,775
		SOC	9180	27540	9180 *
Manufacturing		Production level	204	204	204
		Material Order	150,369 (RM4)	805,545 (RM2) 27,645 (RM3)	150,369 (RM4)
Resources	Tech.	Oven:	6	4	6
		Vacuum:	6	4	6
		Workforce	2	3	2
Costs (€)		Raw Materials	494,035,378	659,063,408	494,035,378
		Technologies (v.)	204,581,946	136,387,964	204,581,946
		Labour (v.)	1,534,378	2,301,566	1,534,378
		Transportation	18,665,451	18,583,937	30,655,792
		Total	948,701,633	969,593,196	960,691,974
		Cost Unit	239,916	270,116	243,834

and appeared as the overall least attractive option throughout the economic analyses. Changing from the economic optimum, VBO, to the most environment-friendly option, VARI, the NPC is around 11% higher for a 50% reduction in environmental impact. This decision to select VARI would imply a social performance three times worse than if VBO is chosen, so it depends on the profile of the decision maker and preferences towards one of the objectives. Regarding the social objective, model decisions and costs associated are very similar to the economic optimum, with costs increasing essentially in transportation despite the use of penalising values for transport modes and technologies.

It is important to compare values obtained with a few estimates provided by Embraer. From table 6.3, it can be verified that costs with raw materials represent between 52% to 68% of total costs, whereas costs with resources fall between 14% and 21%, explaining 66% up to 89% of total cost. According to Embraer, around 51% of unit cost is the average value spent with raw materials and 32% is the amount spent with resources, explaining up to 83% from total cost of one part made out of CFRP. These reference values correspond to a horizontal/vertical stabiliser of Embraer's Legacy 450/500, whose dimensions are different but cost relations are said to be comparable.

Seeing these results, one of the biggest limitations of studying the model for the baseline case is that both environmental and social dimensions are poorly characterised due to lack of data. Hence, the respective objective functions are oversimplified and some key factors to consider in decisions are left out of the problem. Namely, decisions related to tooling that are important for any CFRP-related problem, and costs and impacts associated with facilities that are also a considerable part of any network design.

Several attempts to run a bi-objective optimisation were tried, using both ϵ-constraint and weighted-sum methods. However, lack of data and very simple environmental and social objective functions make it harder to draw meaningful conclusions for this bi-objective analysis.

As seen earlier, there are multiple factors that could change the results for the economic objective, given that TA and VBO have similar performances and the actual optimum is defined by the assumptions and parameters considered. The great amount of uncertainty surrounding the processes other than TA also increases the difficulty in comparing forming processes with a higher degree of confidence. Aerospace industry is still attached to TA because the technology is consolidated and investments in equipment for TA are considered sunk costs.

All in all, the recommendation from this research would be to study the adoption of VBO as a promising technology that meets economic performance standards comparable to those of TA. VBO even presents an acceptable environmental impact, much lower than TA. Nevertheless, TA appears to maintain a competitive economic performance and should not be discarded by the industry but rather perfected for better environmental impact. Regarding transportation, there are no surprising findings seeing it was already expected a global supply chain would require a multi-modal transportation system.

As for computational results, annexed table C.2 demonstrates even though model's complexity in terms of the number of equations and variables, most of the runs are relatively fast and do not represent a constraint for this particular case study.

Having presented the general discussion of results and main recommendations, the next chapter is dedicated to the conclusions of all work developed.

7 | Conclusions and Future Work

Aircraft are incredibly sophisticated products that can operate for more than 30 years. Thus, it is not surprising that the aerospace industry and SC are also incredibly complex networks, with deep supplier involvement at different steps of the product lifecycle. Modularisation of aircraft and low throughput enabled OEMs to outsource complete subsystems, aiming at cost-effectiveness and focus on core competencies. This model of systems' integrator is preferred by manufacturers; albeit with some reservations that key competencies should be kept internal.

In their market forecast for the next two decades, OEMs expect consistent passenger traffic growth, increasing demand for aircraft and forcing the industry to 'unprecedented production ramp-ups'. The magnitude of backlogs is also pushing OEMs to achieve a shorter time-to-market and to find new ways of raising production throughput. Rising jet fuel prices have been forcing airlines to demand lightweight aircraft, pushing the development of advanced materials. The ability to select properties of materials, by design, is a primary driver for advanced materials. However, the additional constraints in development, manufacturing and certification are adverse factors to broader adoption of such materials. A particular type of these advanced materials, the CFRPs, starts from a one-dimensional reinforcement that must be formed resulting in two- or three-dimensional solid parts with the desired shapes and strengths.

Aligned with the research by IAMAT on the pursuit of a framework to assess the appropriate manufacturing process for the aerospace CFRP SC, this dissertation focuses only on four forming processes. Emphasis is put on Out-of-Autoclave (OoA) technologies as potential cost reduction factors and comparison with existing technologies, thus the forming processes considered are (1) Traditional Autoclaving (TA), (2) Vacuum-Assisted Resin Infusion (VARI), (3) Vacuum-Bag Only (VBO) and (4) Thermo-Stamping (TS). The case of Embraer is also presented as the company is interested in studying OoA technologies for CFRP-made aerostructures and verifying its impact on their existing SC. Even though the four alternatives are under study, the industrial partner - Embraer - currently only employs the TA, whereas other processes are developed in the laboratory - with the research partner INEGI.

The primary goal of this master's dissertation is to help closing the identified research gap for sustainable SC optimisation models designed for the aerospace industry that account for the introduction of these new materials. The research question linked to this is to find out which manufacturing process should be adopted by the aerospace industry for composite CFRP parts, based on sustainable performance measures. The research objectives include getting acquainted with the aerospace industry and supply chain, acquire a deeper understanding of advanced materials, contribute to the academic community in the proposed field, help solving the problem identified and develop the skillset and awareness typical of research projects. To accomplish what is proposed, a compact yet thorough and exhaustive literature review is provided on relevant topics such as the aerospace industry, advanced materials, product development, cost estimation, supply chain management, optimisation and sustainability issues. A Mixed-Integer Programming (MIP) model is proposed for aiding on decisions of global network SC design for CFRP manufacturing in aerospace industries. In general, the model considers a (1) superstructure of entities and existing or potentially new geographical locations, a (2) transportation network, the (3) distance between all entities/locations, a (4) set of resources, materials, technologies, and time constraints, and respective manufacturing needs, (5) a set of alternative manufacturing processes, and the (6) costs and social and environmental impacts for all of decisions. This model is based on sustainable performance measures, thus aiming at maximising economic return, and minimising environmental and social impacts.

For the economic objective, based on the NPV, only the manufacturing and marketing stages of the Lifecycle Costing (LCC) are considered, which include costs with material, facilities, production and distribution, due to lack of information and knowledge regarding other stages. Similar boundaries apply to the environmental and the social objective functions, even though with more simplifications for aspects related to transportation. The forming process for the economic optimum is VBO due to lower investment costs and lower price of materials, and implies making use of dedicated workers, and acquiring ovens and vacuum machines. Transportation of raw materials from suppliers to the factory requires refrigerated trucks, whereas the flow from the factory to the OEM is done by ship with the connections from seaports to end-points being done by special-sized trucks.

Thermal forming techniques are highly limited in terms of geometries and size of parts, and before being a possibility in industrial setting more research and technology developments on the process are required. However, TS is presented as the new optimal solution if included as an alternative process, viable for smaller parts. Additional economic analyses are described for key factors subject to uncertainty or assumed such as the (1) scale-up relation between time of process in laboratory and industrial process, (2) demand, (3) batch size and (4) part length. It is discussed that these parameters have considerable influence in the model, hindering the decision of the optimal process. Despite the complex relations between different cost factors, VARI appears as the least attractive option, and TA and VBO concur for the leading option.

For the environmental objective, the ReCiPE2008 method for the Lifecycle Assessment (LCA) is used but only the Global Warming midpoint category is considered. Resorting to a complete database from SimaPro with information from GHG emissions, impact parameters are estimated. The worst environmental performance belongs to TA mostly due to the use of energy-intensive autoclave curing, whereas both VARI and VBO resort to an oven with much lower impact. The process with the optimal environmental performance is VARI, being the process with the lowest impacts per unit of raw materials. Given the environmental impact for resin infusion is lower than that of producing *prepreg*, not even the greater quantities of raw material needed for VARI and which have to be transported is sufficient to offset the benefits. The model of eco-costs is used for the economic valuation of GHG emissions, converting the environmental impact, in $kg\ CO_2$e, to an economic penalty, in €. Although, values for environmental impact appear overestimated and require a more detailed analysis.

A framework for assessing the social impact is constructed for the social objective, with focus on occupational health and workers safety, that allows to distinguish forming processes for their dangerous and/or physically demanding tasks in several qualitative indicators. Different categories are selected based on findings from literature and relevance for CFRP manufacturing processes. Most social assessment techniques are based on *a posteriori* evaluation and lagging indicators, thus the need for a tool for prior assessment and help in decision making. The respective optimal process is VBO, yet the results are highly dependent on the social scores assigned by the framework. The naïve approach developed is applied only to manufacturing but the analysis could be extended to other important social impact factors, such as transportation and warehousing.

The existence of contrasting objectives is discussed, where VBO is the optimal forming process for economic and social objectives and VARI is the process to go when aiming to minimise environmental impact. According to results presented, to change from the economic optimum, VBO, to the most environment-friendly option, VARI, the NPC is around 11% higher for a 50% reduction in environmental impact. The decision to select VARI would imply a social performance three times worse than if VBO is chosen, so it depends on the profile of the decision maker and preferences towards one of the objectives.

Given the limited scope and timeframe for this research, several assumptions and simplifications are required to overcome the problems of lack of data and uncertainty in the estimation of parameters. This results in multiple intended and unintended limitations of the work developed that should be highlighted. Beginning with the simple linear relations used for scaling and batch size values, which strongly restricts the results. Poor characterization of modes of transport, disregard of lead times, transit times or configuration times of any type are limiting factors. It is also assumed materials have no expiry date and there are no restrictions of shelf-life. The production level being equal to demand and this demand not changing over time is another example of these limitations. Moreover, the inability to decide on new locations for facilities is a particular limitation of the case study. In addition, several attempts to run a bi-objective optimisation were tried, using both ϵ-constraint and weighted-sum methods. However, objective environmental and social functions have proved to be too simple and lacking sufficient possible decisions to generate alternative efficient solutions. This reinforces the bias towards economic performance measures, yet could not be avoided based on modelable parameters and available information.

All in all, the main contributions of this work are (1) a proposed model for SC network design and CFRP process selection dedicated to the aerospace industry, (2) the model proposed as a tool for testing different scenarios and impact of parameters, (3) the initial groundbreaking work with a framework for social impact assessment in composites manufacturing and (4) the discussion of alternative OoA forming techniques and the optimal process for a baseline case presented.

In addition to overcoming the limitations identified throughout the document, several suggestions are made for future work based on findings and knowledge acquired in the present research. It would be of value to broaden the scope of the research and include more aspects and factors to be considered for each objective, namely from other tiers of the SC. A more thorough and accurate characterisation of environmental and social aspects is considered a natural next step, with a focus on more robust impact assessment and scores (e.g., based on exhaustive surveys to industry players). The inclusion of a complete LCA instead of the partial GHG emissions would be beneficial for the environmental objective. The development of these two objective functions is another issue of interest and, possibly, the inclusion of another objective based on risk assessment and management as suggested by the literature review. Other smaller ventures could include an economic analysis with values for the annual revenue, studying the effect of the learning curve/productivity on the optimal forming processes, the inclusion of micro-time units for optimising production planning in the manufacturing level (i.e., 2-step optimisation process).

Bibliography

Adler, P. S. (1995), 'Interdepartmental Interdependence and Coordination: The Case of the Design/Manufacturing Interface', *Organization Science* **6**(2), 147–167.
URL: *http://pubsonline.informs.org/doi/abs/10.1287/orsc.6.2.147* 31

Advani, S. G. and Hsiao, K.-T. (2012), *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*.
URL: *http://www.sciencedirect.com/science/article/pii/B978085709067650002X* 13, 14, 16

Ageorges, C. and Ye, L. (2002), *Fusion Bonding of Polymer Composites*.
URL: *http://dx.doi.org/10.1007/978-1-4471-0171-0* 13, 14

Agyapong-Kodua, K., Asare, K. B. and Ceglarek, D. J. (2014), 'Digital modelling methodology for effective cost assessment', *Procedia CIRP* **17**, 744–749.
URL: *http://dx.doi.org/10.1016/j.procir.2014.02.043* 20

Agyapong-Kodua, K., Wahid, B. M. and Weston, R. H. (2011), 'Towards the derivation of an integrated process cost-modelling technique for complex manufacturing systems', *International Journal of Production Research* **49**(24), 7361–7377.
URL: *http://dx.doi.org/10.1080/00207543.2010.535861* 20, 21

Ahi, P. and Searcy, C. (2013), 'A comparative literature analysis of definitions for green and sustainable supply chain management', *Journal of Cleaner Production* **52**, 329–341.
URL: *http://dx.doi.org/10.1016/j.jclepro.2013.02.018* 24

Airbus (2017), Global Market Forecast 2017-2036, Technical report.
URL: *http://www.airbus.com/aircraft/market/global-market-forecast.html* 6

Alçada-Almeida, L., Coutinho-Rodrigues, J. and Current, J. (2009), 'A multiobjective modeling approach to locating incinerators', *Socio-Economic Planning Sciences* **43**(2), 111–120.
URL: *https://doi.org/10.1016/j.seps.2008.02.008* 25

Alting, L. (1991), 'Life-cycle design of products: a new opportunity for manufacturing enterprises'. 10

APICS (2017), 'APICS Dictionary'.
URL: *http://www.apics.org/apics-for-individuals/publications-and-research/apics-dictionary* 7

Ashby, M. F., Bush, S. F., Swindells, N., Bullough, R., Ellison, G., Lindblom, Y., Cahn, R. W. and Barnes, J. F. (1987), 'Technology of the 1990s: Advanced Materials and Predictive Design [and Discussion]', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **322**(1567), 393–407.
URL: *http://dx.doi.org/10.1098/rsta.1987.0059* 12, 13

Asiedu, Y. and Gu, P. (1998), 'Product life cycle cost analysis: State of the art review', *International Journal of Production Research* **36**(4), 883–908.
URL: *http://dx.doi.org/10.1080/002075498193444* 10, 11, 21, 22

ATAG (2005), The economic & social benefits of air transport, Technical report.
URL: *www.icao.int/Meetings/wrdss2011/Documents/JointWorkshop2005/ATAG_SocialBenefitsAirTransport.pdf* 1

Ayers, J. (2001), *Handbook of Supply Chain Management*. 7

Baillie, C. (2004), *Green composites: Polymer composites and the environment*. 17, 18, 58

Baker, A., Dutton, S. and Kelly, D. (2004), *Composite Materials for Aircraft Structures*, 2 edn. 12, 15, 58

Bales, R., Maull, R. and Radnor, Z. (2004), 'The development of supply chain management within the aerospace manufacturing sector', *Supply Chain Management: An International Journal* **9**(3), 250–255.
URL: *http://www.emeraldinsight.com/doi/10.1108/13598540410544944* 7, 8

Ball, P. D., Roberts, S., Natalicchio, A. and Scorzafave, C. (2010), Modelling production ramp-up of engineering products, *in* 'IMechE Vol. 225 Part B: J. Engineering Manufacture', Vol. 225, pp. 959–971.
URL: *http://dx.doi.org/10.1177/09544054JEM2071* 31

Ballou, R. H. and Masters, J. M. (1993), ‘Commercial Software for Locating Warehouses and Other Facilities’, *Journal of Business Logistics* **14**(2), 71–108.
URL: *www.researchgate.net/publication/291049864* 26, 27

Ballou, R. H. and Masters, J. M. (1999), ‘Facility Location Commercial Software Survey.’, *Journal of Business Logistics* **20**(1), 215–233.
URL: *www.researchgate.net/publication/291049968* 26, 27

Baloff, N. (1966), ‘The Learning Curve - Some Controversial Issues’, **14**(3), 275–282. 31

Barbosa-Póvoa, A. P., da Silva, C. and Carvalho, A. (2018), ‘Opportunities and challenges in sustainable supply chain: An operations research perspective’, *European Journal of Operational Research* .
URL: *http://dx.doi.org/10.1016/j.ejor.2017.10.036* 23, 24, 25, 26, 38

Barclays (2015), ‘Environmental and Social Risk Management - General Manufacturing’, *Barclays* **6**(10/16/2011). 40

Barlow, D. A., Scott, M. L., Clayton, G., Havilland, H. D., Melbourne, P., Composite, C. F. and Model, F. E. (2002), Calculating the Cost of a Carbon Fibre Composite Structure From Within a Finite Element Model, pp. 1–10.
URL: *http://www.icas.org/ICAS_ARCHIVE/ICAS2002/PAPERS/R62.PDF* 23

Bassetto, S., Fiegenwald, V., Cholez, C. and Mangione, F. (2011), ‘European Journal of Engineering Experiencing production ramp-up education for engineers’, (October 2014), 37–41. 31

Bellgran, M. and Säfsten, K. (2010), *Production Development: Design and Operation of Production Systems*.
URL: *http://link.springer.com/content/pdf/10.1007/978-1-84882-495-9.pdf* 30, 31, 58

Benkard, C. L. (2000), ‘Learning and Forgetting: The Dynamics of Aircraft Production’, *American Economic Review* **90**(4), 1034–1054.
URL: *http://pubs.aeaweb.org/doi/10.1257/aer.90.4.1034* 31

Berg, M. and Säfsten, K. (2005), Managing Production Ramp-up - Requirement on strategy content, *in* ‘POMS International 2006’, Shanghai, China.
URL: *https://www.pomsmeetings.org/confpapers/005/005-0024.pdf* 30

Bianchi, F. and Pozzi, S. (2011), ‘International Trade Costs and Transportation Modes : The Case of Europe’. 62

Bloemhof-Ruwaard, J., Van Wassenhove, L., Gabel, H. and Weaver, P. (1996), ‘An environmental life cycle optimization model for the European pulp and paper industry’, *Omega* **24**(6), 615–629. 25

Bloor, M., Thomas, M. and Lane, T. (2000), ‘Health risks in the global shipping industry: An overview’, *Health, Risk and Society* **2**(3), 329–340. 39

Boehm, B. W., B. W. Boehm and Boehm, B. W. (1981), ‘Software Engineering Economics’, *Englewood Cliffs, Prentice-Hall, Inc* **22**(5), 269–280.
URL: *http://dx.doi.org/10.1109/TSE.1984.5010193* 18, 19

Boeing (2014), ‘Current Market Outlook 2014 - 2033’. 6

Boeing (2017), ‘Current Market Outlook 2017 - 2036’. 6

Bombardier (2016), Business aircraft market forecast 2016-2025, Technical report.
URL: *http://businessaircraft.bombardier.com/fr/ownership/marketforecast.html* 6

Bozdogan, K., Deyst, J., Hoult, D. and Lucas, M. (1998), ‘Architectural innovation in product development through early supplier integration’, *R and D Management* **28**(3), 163–173.
URL: *http://doi.wiley.com/10.1111/1467-9310.00093* 7

Brigante, D. (2014), *New Composite Materials*.
URL: *http://dx.doi.org/10.1007/978-3-319-01637-5* 12, 13, 14, 15, 64, 74

Caramia, M. and Dell’Olmo, P. (2008), Multi-objective Optimization, *in* ‘Multi-objective Management in Freight Logistics’, pp. 11–37.

URL: *https://en.wikipedia.org/wiki/Multi-objective_optimization* 27

Carter, C. R. and Rogers, D. S. (2008), ‘A framework of sustainable supply chain management: moving toward new theory’, *International Journal of Physical Distribution & Logistics Management* **45**(7), 652–673. 23, 24

Carvalho, A., Filipa, A., Nobre, A. and Matos, H. A. (2014), ‘From a literature review to a framework for environmental process impact assessment index’, *Journal of Cleaner Production* **64**, 36–62.
URL: *http://dx.doi.org/10.1016/j.jclepro.2013.08.010* 25

Centea, T., Grunenfelder, L. K. and Nutt, S. R. (2014), ‘A review of out-of-autoclave prepregs - material properties, process phenomena and manufacturing considerations’, *Compos Part A Appl Sci Manuf* pp. 132–154.
URL: *http://www.sciencedirect.com/science/article/pii/S1359835X14003108* 16, 17

Centea, T. and Nutt, S. R. (2015), ‘Manufacturing cost relationships for vacuum bag-only prepreg processing’, *Journal of Composite Materials* . 16

Chaabane, A., Ramudhin, A. and Paquet, M. (2017), ‘The Management of Operations Designing supply chains with sustainability considerations’, **7287**(December). 24, 25

Chang, Y. (2006), Getting Ahead in Sourcing Through Benchmarking and System Dynamics Analysis: An Aerospace Industry Perspective, Thesis, Massachusetts Institute of Technology (MIT). 5, 7, 8

Chopra, S. and Meindl, P. (2013), *Supply Chain Management - Strategy, Planning and Operation*, 5 edn. 23

Clearwater (2011), ‘Aerospace Global Report 2011’.
URL: *http://www.imap.com/imap/media/resources/Aerospace_8_1FED752787A1E.pdf* 5

Cooper, R. G. and Kleinschmidt, E. J. (1995), ‘Benchmarking the firm’s critical success factors in new product development’, *Journal of Product Innovation Management* **12**(5), 374–391.
URL: *http://www.sciencedirect.com/science/article/pii/0737678295000593* 29

Curran, R., Price, M., Raghunathan, S., Benard, E., Crosby, S., Castagne, S. and Mawhinney, P. (2005), ‘Integrating Aircraft Cost Modeling into Conceptual Design’, *Concurrent Engineering* **13**(4), 321–330. 22

Curran, R., Raghunathan, S. and Price, M. (2004), ‘Review of aerospace engineering cost modelling: The genetic causal approach’, *Progress in Aerospace Sciences* **40**(8), 487–534.
URL: *http://dx.doi.org/10.1016/j.paerosci.2004.10.001* 18, 19, 20, 21

Das, S. (2010), Recycling and life cycle issues for lightweight vehicles, *in* ‘Materials, Design and Manufacturing for Lightweight Vehicles’.
URL: *http://dx.doi.org/10.1533/9781845697822.2.309* 18

Department for Environment, Food and Rural Affairs (2008), ‘Energy and carbon conversions - Calculating your carbon emissions’, *Carbon* pp. 1–6. 63

Dieter, G. E. and Schmidt, L. C. (2009), *Engineering Design*, 4th edn, McGraw-Hill Higher Education, New York. 10

Dočekalová, M. (2013), ‘Construction of corporate social performance indicators for Czech manufacturing industry’, *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* **61**(2), 309–315.
URL: *https://acta.mendelu.cz/61/2/0309/* 38, 40

Duran, O., Rodriguez, N. and Consalter, L. A. (2009), ‘Neural networks for cost estimation of shell and tube heat exchangers’, *Expert Systems with Applications* **36**(4), 7435–7440.
URL: *http://dx.doi.org/10.1016/j.eswa.2008.09.014* 19

Echtelt, V. (2004), New product development: shifting suppliers into gear, Thesis, Technische Universiteit Eindhoven. 32

Elkington, J. (2004), Enter the triple bottom line, *in* ‘The Triple Bottom Line: Does it All Add Up’, Vol. 1, pp. 1–16. 24

Elstner, S. and Krause, D. (2012), Towards an early consideration of ramp-up phase in the product development of complex products, *in* 'Proceedings of International Design Conference - Design 2012', Vol. DS 70, pp. 859–868. 33

Embraer (2017*a*), Annual Report 2017, Technical report. 54, 56

Embraer (2017*b*), Market Outlook 2017-2036, Technical report. 6

Emiliani, M. L. (2003), 'Sourcing in the global aerospace supply chain using online reverse auctions', *Industrial Marketing Management* **33**(1), 65–72. 6, 7

Eskandarpour, M., Dejax, P., Miemczyk, J. and Péton, O. (2015), 'Sustainable supply chain network design: An optimization-oriented review', *Omega (United Kingdom)* **54**, 11–32.
URL: *http://dx.doi.org/10.1016/j.omega.2015.01.006* 38, 63

EU-OSHA (2011), *OSH in figures: Occupational safety and health in the transport sector — An overview*. 39, 40

European Commission (2011), Flightpath 2050 - Europe's Vision for Aviation, Technical report.
URL: *http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf* 1, 25

European Commission (2013), *General Union Environment Action Programme to 2020*. 24

Fabrycky, W. J. and Blanchard, B. S. (1991), Life Cycle Cost and Economic Analysis, *in* '1985 Annual International Industrial Engineering Conference Proceedings', Prentice Hall, pp. 381–391.
URL: *https://www.researchgate.net/publication/239223378* 22

Febeliano, A. (2008), A Revigoração da Indústria da Aviação Geral: Cenários para o Desenvolvimento do Setor, Thesis, Instituto Tecnológico de Aeronáutica - ITA, Brasil.
URL: *http://www.bdita.bibl.ita.br/tesesdigitais/lista_resumo.php?num_tese=000556308* 1

Fitzgerald, W. B., Howitt, O. J., Smith, I. J. and Hume, A. (2011), 'Energy use of integral refrigerated containers in maritime transportation', *Energy Policy* **39**(4), 1885–1896. 64

Freeman, W. (1992), COSTADE, Technical report. 23

Frota Neto, J. Q., Nunen, J. A. E. E. V. and Heck, E. V. (2008), 'Designing and evaluating sustainable logistics networks', **111**, 195–208. 25

Funo, K. A., Muniz, J., Augusto, F. and Marins, S. (2013), 'Fatores de risco em cadeia de suprimentos do setor aeroespacial: aspectos qualitativos e quantitativos', pp. 832–845. 10

Gates, D. (2011), 'A 'prescient' warning to Boeing on 787 trouble', *The Seattle Times* .
URL: *http://old.seattletimes.com/html/sundaybuzz/2014125414_sundaybuzz06.html* 10

Gay, D., Hoa, S. V. and Tsai, S. W. (2003), *Composite materials and applications*, CRC Press, Paris. 13, 15, 58, 65

Glas, M. and Ziemer, S. (2009), Challenges for agile development of large systems in the aviation industry, *in* 'Proceeding of the 24th ACM SIGPLAN conference companion on Object oriented programming systems languages and applications - OOPSLA '09', p. 901.
URL: *http://dl.acm.org/citation.cfm?doid=1639950.1640054* 28

Global Reporting Initiative (2014), 'G4 Sustainability Reporting Guidelines', *Global Reporting Initiative* pp. 1–97.
URL: *https://www.globalreporting.org/standards/g4/Pages/default.aspx* 39

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Struijs, J. and van Zelm, R. (2008), 'Recipe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level', (5), 31. 25, 37, 38

Goetschalckx, M. (2011), *Supply Chain Engineering*, Vol. 161 of *International Series in Operations Research & Management Science*, Springer US, Boston, MA.
URL: *http://link.springer.com/10.1007/978-1-4419-6512-7* 26, 27, 60, 68

Gomes, A. C. d. S. M., Paula, A., Dias, F. and Póvoa, B. (2016), 'Optimization of supply chain network design and planning under recent trends A food supply chain Ana Carla de Souza Marques Gomes

Thesis to obtain the Master of Science Degree in Industrial Engineering and Management Supervisor : Prof . Tânia Rute Xavier', (June). 59

González, C., Vilatela, J. J., Molina-Aldareguía, J., Lopes, C. and LLorca, J. (2017), 'Structural composites for multifunctional applications: Current challenges and future trends', *Progress in Materials Science* **89**, 194–251.
URL: *http://dx.doi.org/10.1016/j.pmatsci.2017.04.005* 14, 16, 65, 66

Goodship, V. (2010), *Management , recycling and reuse of waste composites*, CRC Press. 17

Gopalakrishnan, K., Yusuf, Y. Y., Musa, A., Abubakar, T. and Ambursa, H. M. (2012), 'Sustainable supply chain management: A case study of British Aerospace (BAe) Systems', *International Journal of Production Economics* **140**(1), 193–203.
URL: *http://dx.doi.org/10.1016/j.ijpe.2012.01.003* 23, 24, 25, 26

Goren, A. and Atas, C. (2008), 'Manufacturing of polymer matrix composites using vacuum assisted resin infusion molding', *Archives of Materials Science and Engineering* **34**(2), 117–120. 16

Gostic, W. J. (1998), Aerospace Supply Chain Management, Thesis, Massachusetts Institute of Technology (MIT). 7, 8

Graham, G. and Ahmed, P. (2000), 'Buyer-supplier management in the aerospace value chain', *Integrated Manufacturing Systems* **11**(July), 462–468.
URL: *http://dx.doi.org/10.1108/09576060010349767* 28

Guadix, J., Carrillo-Castrillo, J., Onieva, L. and Lucena, D. (2015), 'Strategies for psychosocial risk management in manufacturing', *Journal of Business Research* **68**(7), 1475–1480.
URL: *http://dx.doi.org/10.1016/j.jbusres.2015.01.037* 39

Guerra, J. H. L. (2011), 'O modelo de integração de sistemas da indústria aeronáutica: fatores motivadores', *Gestão & Produção* **18**(2), 251–264.
URL: *http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-530X2011000200003&lng=pt&tlng=pt* 9, 10

Handfield, R. B., Ragatz, G. L., Petersen, K. J. and Monczka, R. M. (1999), 'Involving Suppliers in New Product Development', *California Management Review* **42**(1), 59–82.
URL: *http://journals.sagepub.com/doi/10.2307/41166019* 27, 28, 32

Haresceugh, R., Bowen, D., Bonfield, W., Hodgson, A., Gent, A., Livingston, D. and Beardmore, P. (1994), Aircraft and Aerospace Applications of Composites, *in* A. Kelly, ed., 'Concise Encyclopedia of Composite Materials', Elsevier, pp. 1–31.
URL: *http://linkinghub.elsevier.com/retrieve/pii/B9780080423005500121* 14

Harland, C. M. (1996), 'Supply Chain Management: Relationships, Chains and Networks', *British Journal of Management* **7**(s1), S63–S80.
URL: *http://doi.wiley.com/10.1111/j.1467-8551.1996.tb00148.x* 7, 8

Harland, C. M., Lamming, R. C. and Cousins, P. D. (1999), 'Developing the concept of supply strategy', *International Journal of Operations & Production Management* **19**(7), 650–674.
URL: *http://www.emeraldinsight.com/doi/10.1108/01443579910278910* 7

Hart, C. G., He, Z., Sbragio, R. and Vlahopoulos, N. (2012), 'An Advanced Cost Estimation Methodology for Engineering Systems', **15**(1). 20

Heljedal, M. (2013), *Factors Influencing the Choice between Road and Multimodal Transportation*, number 1. 60

Henao, R., Sarache, W. and Gomez, I. (2017), 'Social Performance Metrics for Manufacturing Industry', (July), 1–10. 39, 40

Hexcel (2015), HexFlow ® RTM6-2 Resin - Data Sheet, Technical report.
URL: *http://www.hexcel.com/Resources/DataSheets/RTM-Data-Sheets/RTM6-2_eu.pdf* 56, 57, 63

Hexcel (2016*a*), HexPly ® M21 Prepreg - Product Data Sheet, Technical report.
URL: *http://www.hexcel.com* 56, 57, 63, 72

Hexcel (2016*b*), HiTape ® HexTow Dry Fibre - Data Sheet, Technical report.
URL: *http://www.hexcel.com* 56, 57, 63

Hexcel (2017), HexPly ® M56 Prepreg - Product Data Sheet, Technical report.
URL: *http://www.hexcel.com* 56, 57, 63

Higham, R. (1968), 'Quantity vs. Quality : The Impact of Changing Demand on the British Aircraft Industry, 1900-1960', *The Business History Review* **42**(4), 443–466.
URL: *http://www.jstor.org/stable/10.2307/3112528* 7, 8

Hilier, F. and Lieberman, G. (2015), *Introduction to Operational Research*, number i. 26, 27

Horng, T.-C. (2006), A comparative analysis of supply chain management practices by Boeing and Airbus: long-term strategic implications, Thesis, Massachusetts Institute of Technology (MIT).
URL: *http://dspace.mit.edu/handle/1721.1/38579* 6

Hueber, C., Horejsi, K. and Schledjewski, R. (2016), 'Review of cost estimation: methods and models for aerospace composite manufacturing', *Advanced Manufacturing: Polymer & Composites Science* **2**(1), 1–13.
URL: *http://www.tandfonline.com/doi/full/10.1080/20550340.2016.1154642* 21, 23

Hugo, A. and Pistikopoulos, E. N. (2005), 'Environmentally conscious long-range planning and design of supply chain networks', *Journal of Cleaner Production* **13**(15), 1428–1448. 25

IAMAT (2017), 'IAMAT - Introduction of Advanced Materials Technologies Into New Product Development for the Mobility Industries', pp. 1–17. 2, 13, 15, 34, 37

IATA (2017), Fact Sheet: Industry Statistics, Technical Report 20-12-2008.
URL: *http://www.iata.org/NR/rdonlyres/8BDAFB17-EED8-45D3-92E2-590CD87A3144/0/FactSheetIndustryFactsDEC2008.pdf* 1

Ibsen, A. Z. (2009), 'Technology in Society The politics of airplane production : The emergence of two technological frames in the competition between Boeing and Airbus', *Technology in Society* **31**(4), 342–349.
URL: *http://dx.doi.org/10.1016/j.techsoc.2009.10.006* 5

ICAO (2004), 'Manual on the Regulation of International Air Transport Manual on the Regulation of International Air Transport'. 5, 6

ICEAA (n.d.), 'International Cost Estimating and Analysis Association - Glossary'.
URL: *http://www.iceaaonline.com/* 18

Industrial Custom Products Inc. (2017), 'Large Part Thermoforming'.
URL: *http://www.industrialcustom.com/large-part-thermoforming.html* 71

Isenberg, R. (2012), 'SMART ramp-up : methods to secure production ramp-up in the aircraft industry', pp. 125–134. 30, 32, 33

Javadi, S., Bruch, J. and Bellgran, M. (2016), 'Characteristics of product introduction process in low-volume manufacturing industries', *Journal of Manufacturing Technology Management* **27**(4), 535–559.
URL: *http://www.emeraldinsight.com/doi/10.1108/JMTM-03-2015-0017* 30, 31

Javadi, S., Bruch, J., Bellgran, M. and Hallemark, P. (2013), Challenges in the industrialization process of low-volume production systems, number September, pp. 19–20. 30

Jha, A., Lupashin, S. and Pun, A. (2007), Cost-Based Design Optimization of a Structure using a Genetic Algorithm, *in* '48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference', number April, American Institute of Aeronautics and Astronautics, Reston, Virigina, pp. 1–12.
URL: *http://arc.aiaa.org/doi/10.2514/6.2007-1910* 21

Johansen, K. (2005), Collaborative product introduction within extended enterprises, Thesis, Linkopings University. 30

Johnsen, T. E. (2009), 'Supplier involvement in new product development and innovation: Taking stock and looking to the future', *Journal of Purchasing and Supply Management* **15**(3), 187–197.
URL: *http://dx.doi.org/10.1016/j.pursup.2009.03.008* 28

Johnson, G., Whittington, R., Scholes, K., Angwin, D. and Regnér, P. (2014), *Exploring Strategy*, 10th edn, Pearson Education Ltd, Harlow, England. 6, 8, 9, 29

Jones, R. M. and Bert, C. W. (1999), *Mechanics of composite materials*, Vol. 102.
URL: *http://dx.doi.org/10.1016/B978-0-444-99713-5.50002-6* 12

Kazerouni, A. M., Achiche, S., Hisarciklilar, O. and Thomson, V. (2011), 'Appraisal of New Product Development Success Indicators in the Aerospace Industry', *Journal of Mechanical Design* **133**(10), 101013.
URL: *http://dx.doi.org/10.1115/1.4004974* 28

Komoto, H., Tomiyama, T., Silvester, S. and Brezet, H. (2011), 'Analyzing supply chain robustness for OEMs from a life cycle perspective using life cycle simulation', *International Journal of Production Economics* **134**(2), 447–457.
URL: *http://dx.doi.org/10.1016/j.ijpe.2009.11.017* 25

Kriwet, A., Zussman, E. and Seliger, G. (1995), 'Systematic integration of design-for-recycling into product design', *International Journal of Production Economics* **38**(1), 15–22. 10, 11

Lakemond, N., Johansson, G., Magnusson, T. and Safsten, K. (2007), 'Interfaces between technology development, product development and production: critical factors and a conceptual model', *International Journal of Technology Intelligence and Planning* **3**(4), 317.
URL: *http://www.inderscience.com/link.php?id=16303* 31

Land, P., Crossley, R., Branson, D. and Ratchev, S. (2015), 'Technology Review of Thermal Forming Techniques for use in Composite Component Manufacture', *SAE International Journal of Materials and Manufacturing* **9**(1), 2015–01–2610.
URL: *http://papers.sae.org/2015-01-2610/* 71

Le Dain, M. A. and Merminod, V. (2014), 'A knowledge sharing framework for black, grey and white box supplier configurations in new product development', *Technovation* **34**(11), 688–701.
URL: *http://dx.doi.org/10.1016/j.technovation.2014.09.005* 28, 29

Leahy, J., Hollinger, P. and Waldmeir, P. (2018), 'Boeing strikes deal for control of Embraer regional jet operations'.
URL: *https://www.ft.com/content/5ba0c060-8046-11e8-bc55-50daf11b720d* 54

Li, H.-h. J. K., Shi, Y. J., Gregory, M. and Tan, K. H. (2013), 'Rapid production ramp-up capability : a collaborative supply network perspective', (February 2015), 37–41. 31, 32, 33

LIPASTO (2017), 'LIPASTO Unit Emissions database'.
URL: *http://lipasto.vtt.fi/yksikkopaastot/indexe.htm* 64

Liu, G. P., Yang, J.-B. and Whidborne, J. F. (2003), *Multiobjective Optimisation and Control*, Vol. 4. 27

Long, A. C. (2006), *Design and Manufacture of Textile Composites (Woodhead Publishing in Textiles)*.
URL: *http://www.amazon.com/Manufacture-Composites-Woodhead-Publishing-Textiles/dp/0849325935* 26

Ma, W. (2011), Cost modelling for manufacturing of aerospace composites, Thesis, Cranfield University.
URL: *http://dspace.lib.cranfield.ac.uk/handle/1826/6279* 13

Mabson, G. E., Ilcewicz, L. B., Graesser, D. L., Metschan, S. L., Proctor, M. R., Tervo, D. K., Tuttle, M. E. and Zabinsky, Z. B. (1996), 'Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE)'. 23

Maffin, D. and Braiden, P. (2001), 'Manufacturing and supplier roles in product development', *International Journal of Production Economics* **69**(2), 205–213. 31

Månson, J.-A. E., Wakeman, M. D., Bourban, P.-E. and Sunderland, P. W. (1999), Driving forces for cost-effective composites : new demands on materials and processes, *in* 'International Conference on Composite Materials ICCM12'.
URL: *http://iccm-central.org/Proceedings/ICCM12proceedings/site/papers/pap1401.pdf* 17

Manzini, R., Gamberi, M., Gebennini, E. and Regattieri, A. (2008), 'An integrated approach to the design and management of a supply chain system', *International Journal of Advanced Manufacturing Technology* **37**(5-6), 625–640. 26

Marques, A. (2018), Sustainable Alternatives for Logistics in Aerospace, Thesis, Instituto Superior Técnico. 34, 35, 55, 57, 59, 61, 62, 63, 64, 67, 68, 72, 75, B.I

Mårtensson, P., Zenkert, D. and Åkermo, M. (2015), 'Integral versus differential design for high-volume manufacturing of composite structures'. 14, 17

Martinez, M. R. E. (2007), A Globalização Da Indústria Aeronáutica: o caso da Embraer, Thesis, Universidade de Brasília.
URL: *http://www.funag.gov.br/ipri/btd/index.php/9-teses/803-a-globalizacao-da-industria-aeronautica-o-caso-da-embraer* 8, 9

Mazumdar, S. K. (2002), *Composites Manufacturing: Materials, Product and Process Engineering*, Vol. 32.
URL: *http://linkinghub.elsevier.com/retrieve/pii/0010436170903162* 12, 15, 65, 74

Mazzola, E., Bruccoleri, M. and Perrone, G. (2015), 'Supply chain of innovation and new product development', *Journal of Purchasing and Supply Management* **21**(4), 273–284.
URL: *http://dx.doi.org/10.1016/j.pursup.2015.04.006* 29

Min, H. and Zhou, G. (2002), 'Supply chain modeling: past, present and future', *Computers & Industrial Engineering* **43**(1-2), 231–249.
URL: *http://linkinghub.elsevier.com/retrieve/pii/S0360835202000669* 27

Mislick, G. K. and Nussbaum, D. A. (2015), *Cost Estimation: Methods and Tools*, John Wiley & Sons, Inc, Hoboken, NJ, USA.
URL: *http://doi.wiley.com/10.1002/9781118802342* 18, 20, 21, 22, 23

Mitschang, P. and Hildebrandt, K. (2012), Polymer and composite moulding technologies for automotive applications, *in* J. Rowe, ed., 'Advanced Materials in Automotive Engineering', Woodhead Publishing Limited, chapter 8, pp. 210–228.
URL: *http://dx.doi.org/10.1533/9780857098993.frontmatter* 13, 14

Montoya-Weiss, M. M. and Calantone, R. (1994), 'Determinants of New Product Performance: A Review and Meta-Analysis', *Journal of Product Innovation Management* **11**(5), 397–417.
URL: *http://doi.wiley.com/10.1111/1540-5885.1150397* 29

Mota, B., Carvalho, A., Gomes, M. and Barbosa-Póvoa, A. (2015), Design and Planning of Sustainable Supply Chains, *in* 'Computer Aided Chemical Engineering', Vol. 36, Elsevier, pp. 333–353.
URL: *http://dx.doi.org/10.1016/B978-0-444-63472-6.00013-6* 23

Mota, B., Gomes, M. and Barbosa-Póvoa, A. (2014), 'Supply chain design towards sustainability: accounting for growth and jobs', *Computer Aided Chemical Engineering* **34**, 789–794.
URL: *http://dx.doi.org/10.1016/B978-0-444-63433-7.50116-4* 24

Mota, B., Gomes, M., Carvalho, A. and Barbosa-Póvoa, A. (2014), 'Towards supply chain sustainability: Economic, environmental and social design and planning', *Journal of Cleaner Production* **105**, 14–27.
URL: *http://dx.doi.org/10.1016/j.jclepro.2014.07.052* 25, 38

Mota, B., Gomes, M., Carvalho, A. and Barbosa-Póvoa, A. (2017), 'Sustainable supply chains: An integrated modeling approach under uncertainty', *Omega* **0**, 1–26.
URL: *http://linkinghub.elsevier.com/retrieve/pii/S0305048317304401* 26, 35, 36, 37, 38, 40, 52, 60, 61, 62

Mowery, D. C. and Rosenberg, N. (1989), *Technology and the pursuit of economic growth*, Vol. 44, Cambridge University Press, Cambridge.
URL: *http://ebooks.cambridge.org/ref/id/CBO9780511664441* 7

Mundt, H.-E. (2003), Long-Term Cooperation in the European Aerospace Industry - A Model for Future Successful Partnering in Competitive Environments, *in* P. Sachsenmeier and M. Schottenloher, eds, 'Challenges Between Competition and Collaboration', p. 59. 5

Nagurney, A., Liu, Z. and Woolley, T. (2007), 'Sustainable Supply Chain and Transportation Networks', *International Journal of Sustainable Transportation* (August 2014), 37–41. 25

Nagurney, A. and Nagurney, L. S. (2010), 'International Journal of Sustainable Engineering Sustainable supply chain network design : a multicriteria perspective', (June 2015), 37–41. 25

Nagurney, A. and Toyasaki, F. (2003), 'Supply chain supernetworks and environmental criteria', *Transportation Research Part D: Transport and Environment* **8**(3), 185–213.
URL: *http://linkinghub.elsevier.com/retrieve/pii/S1361920902000494* 25

Nairn, G. (2005), 'Airline seats have become commodities', *Financial Times* pp. 9–11.
URL: *https://www.ft.com/content/ad233116-f2bf-11d9-8094-00000e2511c8* 1

NASA (2015), 'NASA Cost Estimating Handbook', *Nasa* (4), 63.
URL: *https://www.nasa.gov/offices/ooe/CAD/nasa-cost-estimating-handbook-ceh/#.V5-mQ_xX-70* 20, 21

National Research Council (1999), Trends and Challenges in Aerospace Offsets, *in* C. W. Wessner, ed., 'National Research Council', The National Academies Press, Washington, DC. 9

Newnes, L. B., Mileham, A. R., Cheung, W. M., Marsh, R., Lanham, J. D., Saravi, M. E. and Bradbery, R. W. (2008), 'Predicting the whole-life cost of a product at the conceptual design stage', (April 2015), 37–41.
URL: *http://dx.doi.org/10.1080/09544820701803061* 28

Niazi, A., Dai, J. S., Balabani, S. and Seneviratne, L. (2006), 'Product Cost Estimation: Technique Classification and Methodology Review', *Journal of Manufacturing Science and Engineering* **128**(2), 563.
URL: *http://manufacturingscience.asmedigitalcollection.asme.org/article.aspx?articleid=1450629* 18, 19, 20

Nilsson, L. N. and Vänje, A. (2018), 'Occupational safety and health professionals ' skills – A call for system understanding ? Experiences from a co-operative inquiry within the manufacturing sector', *Applied Ergonomics* **70**(June 2017), 279–287.
URL: *https://doi.org/10.1016/j.apergo.2018.03.005* 39

Niosi, J. and Zhegu, M. (2005*a*), 'Aerospace clusters: Local or global knowledge spillovers?', *Industry and Innovation* **12**(1), 5–29.
URL: *http://www.tandfonline.com/doi/abs/10.1080/1366271042000339049* 5, 6, 7, 8, 9, 26, 29

Niosi, J. and Zhegu, M. (2005*b*), Globalization and the Patterns of Industry Location: the case of the Aerospace Industry, *in* 'Innovation Systems Research Network 7th Annual Meeting'. 7

Niosi, J. and Zhegu, M. (2008), 'Innovation system lifecycle in the aircraft sector', *Entrepreneurship and Innovation–Organizations, Institutions, Systems and Regions, DRUID, Copenhagen, CBS, Denmark* (June). 5, 7, 8, 29

Oliveux, G., Dandy, L. O. and Leeke, G. A. (2015), 'Progress in Materials Science Current status of recycling of fibre reinforced polymers : Review of technologies , reuse and resulting properties', **72**, 61–99. 17, 18

Oregon OSHA (2014), 'Health Hazards Polymer Matrix Materials :', pp. 1–39. 40

Ou-Yang, C. and Lin, T. (1997), 'Developing and Integrated Framework for Feature-Based Early Manufacturing Cost Estimation', *Journal of Advances Manufacturing Technology* **13**, 618–629. 21

Papageorgiou, L. G. and Georgiadis, M. C. (2008), *Process Systems Engineering - Supply Chain Optimization, Part I*, Vol. 3. 60

Petersen, K. J., Handfield, R. B. and Ragatz, G. L. (2005), 'Supplier integration into new product development: Coordinating product, process and supply chain design', *Journal of Operations Management* **23**(3-4), 371–388. 28

Petrick, I. J. (2007), 'Tipping the balance of power: The case of Large Scale Systems Integrators and their supply chains', *International Journal of Foresight and Innovation Policy* **3**(3), 240–255.
URL: *http://dx.doi.org/10.1504/IJFIP.2007.014009* 9

Pickering, S. J. (2004), ‘Recycling Technologies For Thermoset Composite Materials’, *Advanced Polymer Composites for Structural Applications in Construction: ACIC 2004* **37**, 392–399. 17

Popovic, T., Barbosa-Póvoa, A., Kraslawski, A. and Carvalho, A. (2018), ‘Quantitative indicators for social sustainability assessment of supply chains’, *Journal of Cleaner Production* **180**, 748–768. 38, 39

Popovic, T. and Kraslawski, A. (2015), *Social Sustainability of Complex Systems*, Vol. 36, Elsevier.
URL: *http://dx.doi.org/10.1016/B978-0-444-63472-6.00024-0* 38, 39

Popovic, T. and Kraslawski, A. (2017), ‘Quantitative Indicators of Social Sustainability and Determination of Their Interdependencies. Example Analysis for a Wastewater Treatment Plant’, **62**(2), 224–235. 39

PRé (2018), ‘SimaPro Sustainability software’.
URL: *https://www.pre-sustainability.com/sustainability-consulting/sustainable-practices/custom-sustainability-software* 38, 64

Productive Plastics Inc. (2018), ‘Part Size Has a Big Impact When Choosing Between Injection Molding and Plastic Thermoforming’.
URL: *https://www.productiveplastics.com/2018/02/16/part-size-big-impact-choosing-injection-molding-plastic-thermoforming/* 71

Quintana-Amate, S., Bermell-Garcia, P., Tiwari, A. and Turner, C. J. (2017), ‘A new knowledge sourcing framework for knowledge-based engineering: An aerospace industry case study’, *Computers and Industrial Engineering* **104**, 35–50. 28, 29

Ray Products Company Inc. (2017), ‘LARGE PART THERMOFORMING’.
URL: *https://www.rayplastics.com/thermoforming-project-needs/large-part-thermoforming/* 71

Reed, F. M. and Walsh, K. (2002), ‘Enhancing technological capability through supplier development: A study of the U.K. aerospace industry’, *IEEE Transactions on Engineering Management* **49**(3), 231–242. 32

Resetar, S. A., Rogers, J. C. and Hess, R. W. (1991), ‘Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology’.
URL: *http://www.rand.org/pubs/reports/2006/R4016.pdf* 12, 13, 14, 17

Richter, K. and Witt, N. (2017), Supply Chain Integration Challenges in Commercial Aviation, *in* ‘Supply Chain Integration Challenges in Commercial Aerospace’, chapter 1, p. 15.
URL: *http://link.springer.com/10.1007/978-3-319-46155-7* 2, 6

Rink, D. R. and Swan, J. E. (1979), ‘Product life cycle research: A literature review’, *Journal of Business Research* **7**(3), 219–242. 10

Robinson, M. A. (2012), ‘How design engineers spend their time: Job content and task satisfaction’, *Design Studies* **33**(4), 391–425.
URL: *http://dx.doi.org/10.1016/j.destud.2012.03.002* 28

Rose-Anderssen, C., Baldwin, J. and Ridgway, K. (2011), ‘Commercial aerospace supply chains’, *Journal of Manufacturing Technology Management* **22**(1), 66–89.
URL: *https://doi.org/10.1108/17410381111099815* 7, 8

Rose-Anderssen, C., Ridgway, K., Baldwin, J., Allen, P., Varga, L. and Strathern, M. (2008), ‘The evolution of commercial aerospace supply chains and the facilitation of innovation’, *International Journal of Electronic Customer Relationship Management* **2**(1), 63.
URL: *http://www.inderscience.com/link.php?id=19569* 7, 8

Roskam, J. (1985), Part VIII - Airplane Cost Estimation: Design, Development, Manufacturing and Operating, *in* ‘Airplane Design’, chapter Part VIII. 11, 22, 23, 32

Rush, C. and Roy, R. (2000), ‘Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cycle’, *7th ISPE International Conference on Concurrent Engineering: Research and Applications* **44**(0), 58–67. 18

Rybicka, J., Tiwari, A., Alvarez Del Campo, P. and Howarth, J. (2015), ‘Capturing composites manufac-

turing waste flows through process mapping', *Journal of Cleaner Production* **91**, 251–261.
URL: *http://dx.doi.org/10.1016/j.jclepro.2014.12.033* 17, 18

Santos, D. H. (2017), Caracterização e Otimização da Cadeia de Abastecimento Aeronáutica O caso da Embraer, Thesis, Instituto Superior Técnico. 34, 37, 54, 55, 57, 58, 61, 62, 63, 64, 65, 67, 68, 71, 72, 75, A.I, B.I

SBAC and ATKearney (1998), The impact of global aerospace consolidation on UK suppliers, Technical report. 9

Scelsi, L., Bonner, M., Hodzic, A., Soutis, C., Wilson, C., Scaife, R. and Ridgway, K. (2011), 'Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment', *Express Polymer Letters* **5**(3), 209–217. 26

Schmidt, G. and Wilhelm, W. E. (2000), 'Strategic, tactical and operational decisions in multi-national logistics networks: A review and discussion of modelling issues', *International Journal of Production Research* **38**(7), 1501–1523. 26

Schuh, G., Desoi, J. and Tücks, G. (2005), 'Holistic approach for production ramp-up in automotive industry', *Advances in Integrated Desi d gn and Manufacturing in Mechanical Engineering* **49**, 255–268.
URL: *http://link.springer.com/chapter/10.1007/1-4020-3482-2_20* 30

Seuring, S. (2013), 'A review of modeling approaches for sustainable supply chain management', *Decision Support Systems* **54**(4), 1513–1520.
URL: *http://dx.doi.org/10.1016/j.dss.2012.05.053* 24, 25, 38

Seuring, S. and Müller, M. (2008), 'From a literature review to a conceptual framework for sustainable supply chain management', *Journal of Cleaner Production* **16**(15), 1699–1710. 25

Shehab, E. and Abdalla, H. (2002), 'An Intelligent Knowledge-Based System for Product Cost Modelling', pp. 49–65.
URL: *http://dx.doi.org/10.1007/PL00003967* 21

Shehab, E. M. and Abdalla, H. S. (2001), 'Manufacturing cost modelling for concurrent product development', **17**, 341–353.
URL: *http://dx.doi.org/10.1016/S0736-5845(01)00009-6* 21

Silva, J., Nunes, J. P., Bernardo, C. a. and Marques, A. (2011), 'Thermoplastic Matrix Composites from Towpregs', *Advances in Composite Materials - Analysis of Natural and Man-Made Materials2* pp. 307–324.
URL: *http://cdn.intechweb.org/pdfs/18856.pdf* 17

Simchi-Levi, D., Kaminsky, P. and Simchi-Levi, E. (2004), *Managing the supply chain: The definitive guide for the business profesional.* 7

Singh, S., Olugu, E. U. and Musa, S. N. (2016), 'Development of Sustainable Manufacturing Performance Evaluation Expert System for Small and Medium Enterprises', *Procedia CIRP* **40**, 609–614.
URL: *http://dx.doi.org/10.1016/j.procir.2016.01.142* 38

Slayton, R. and Spinardi, G. (2016), 'Radical innovation in scaling up: Boeing's Dreamliner and the challenge of socio-technical transitions', *Technovation* **47**, 47–58.
URL: *http://dx.doi.org/10.1016/j.technovation.2015.08.004* 26

Snudden, J. P., Ward, C. and Potter, K. (2014), 'Reusing automotive composites production waste', *Reinforced Plastics* **58**(6), 20–27.
URL: *http://dx.doi.org/10.1016/S0034-3617(14)70246-2* 17, 18, 57

Society of Cost Estimating and Analysis (2017), 'SCEA GLOSSARY'.
URL: *https://www.sceaonline.org/prof_dev/glossary-c.html* 18

Solvay (2017), APC-2-PEEK Thermoplastic Prepreg - Data Sheet, Technical report. 56, 57, 63

Son, Y. K. (1991), 'A cost estimation model for advanced manufacturing systems', *International Journal of Production Research* **29**(3), 441–452. 20

Stellingwerf, H. M., Kanellopoulos, A., van der Vorst, J. G. and Bloemhof, J. M. (2018), ‘Reducing CO2emissions in temperature-controlled road transportation using the LDVRP model’, *Transportation Research Part D: Transport and Environment* **58**, 80–93.
URL: *https://doi.org/10.1016/j.trd.2017.11.008* 64

Stoycheva, S., Marchese, D., Paul, C., Padoan, S., Juhmani, A.-s. and Linkov, I. (2018), ‘Multi-criteria decision analysis framework for sustainable manufacturing in automotive industry’, *Journal of Cleaner Production* .
URL: *http://linkinghub.elsevier.com/retrieve/pii/S0959652618307947* 39

Surbier, L., Alpan, G. and Blanco, E. (2013), ‘A comparative study on production ramp-up: state-of-the-art and new challenges’, (March 2015), 37–41. 30, 31

Suzuki, T. and Takahashi, J. (2005), ‘Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars’, *Ninth Japan International SAMPE Symposium JISSE-9* pp. 14–19.
URL: *http://j-t.o.oo7.jp/publications/051129/S1-02.pdf* 63

Taha, H. A. (2007), *Operations Research: An Introduction*, 8th edn, Pearson Prentice Hall, New Jersey. 26, 27

Tang, C. S. (2006), ‘Robust strategies for mitigating supply chain disruptions’, **5567**(December).
URL: *http://dx.doi.org/10.1080/13675560500405584* 10

Tang, C., Zimmerman, J. and Nelson, J. (2009), ‘Managing new product development and supply chain risks: The Boeing 787 case’, *Supply Chain Forum: An* **10**(2), 74–86. Taylor & Francis.
URL: *http://dx.doi.org/10.1080/16258312.2009.11517219* 10, 30, 31

Tang, Z. E., Goetschalckx, M. and McGinnis, L. (2013), ‘Modeling-based design of strategic supply chain networks for aircraft manufacturing’, *Procedia Computer Science* **16**, 611–620.
URL: *http://dx.doi.org/10.1016/j.procs.2013.01.064* 27

Terwiesch, C. and Xu, Y. (2004), ‘The copy-exactly ramp-up strategy: Trading-off learning with process change’, *IEEE Transactions on Engineering Management* **51**(1), 70–84. 31

Tretheway, M. W. (2004), ‘Distortions of airline revenues: why the network airline business model is broken’, *Journal of Air Transport Management* **10**(1), 3–14.
URL: *http://linkinghub.elsevier.com/retrieve/pii/S096969970300084X* 1

Treuner, F., Hübner, D., Baur, S. and Wagner, S. M. (2012), ‘Supply Chain Resilience: A Survey of Disruptions in Aviation and Aerospace Supply Chains and Increasing Resilience’, *IPM Supply Chain Management* pp. 7–12. 6, 9, 10

Trott, P. (2005), *Innovation Management and New Product Development*. 29

Tsay, A. A. (2014), ‘Designing and Controlling the Outsourced Supply Chains’, *Foundations and Trends in Technology, Information and Operations Management* **7**(1-2), 1–160.
URL: *http://dx.doi.org/10.1561/0200000030* 10

TU Delft (2012), ‘The Model of the Eco-costs / Value Ratio (EVR)’.
URL: *http://www.ecocostsvalue.com/EVR/model/theory/subject/2-eco-costs.html* 75

UK-HSE (2014), ‘The health and safety toolbox: How to control risks at work’, **268**(published), 103.
URL: *http://www.hse.gov.uk/pubns/priced/hsg268.pdf* 40

Ullman, D. G. (2010), *The Mechanical Design Process*, 4th edn, McGraw-Hill, New York. 21, 31

Ulrich, K. T. and Eppinger, S. D. (2012), *Product Design and Development*. 28

US Department of Defense (1985), Transition from Development to Production, Technical Report September 1985, US Department of Defense. 31

US-OSHA (2011), ‘OSHA Technical Manual - Polymer Matrix Materials’, **Section II**(OSHA Technical Manual), 1–2. 40, 65, 66

Utterback, J. M. and Abernathy, W. J. (1975), ‘A Dynamic Model of Process and Product Innovation’, *Burns* (6), 639–656. 29

van Hattum, F. W. J., Regel, F. and Labordus, M. (2011), 'Cost reduction in manufacturing of aerospace composites', *Plastics, Rubber and Composites* **40**(2), 93–99.
URL: *http://www.tandfonline.com/doi/full/10.1179/174328911X12988622801052* 14

Varghese, B. M., Hansen, A., Bi, P. and Pisaniello, D. (2018), 'Are workers at risk of occupational injuries due to heat exposure ? A comprehensive literature review', *Safety Science* (April), 0–1.
URL: *http://dx.doi.org/10.1016/j.ssci.2018.04.027* 39, 40

Wang, F., Lai, X. and Shi, N. (2011), 'A multi-objective optimization for green supply chain network design', *Decision Support Systems* **51**(2), 262–269.
URL: *http://dx.doi.org/10.1016/j.dss.2010.11.020* 25

WCED (1987), 'Our Common Future: Report of the World Commission on Environment and Development', *United Nations Commission* **4**(1), 300. 23, 24

Wheelwright, S. C. (1984), 'Manufacturing strategy defining the missing link', *Strategic Management Journal* **77-91.**(Fp), Inic. 30

Wheelwright, S. C. and Clark, K. B. (1992), *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency and Quality*, The Free Press, New York. 31

White, G. and Ostwald, P. (1976), 'Life Cycle Costing', *Management Accounting* (January), 39–42. 10

Williams, T., Maull, R. and Ellis, B. (2002), 'Demand chain management theory: Constraints and development from global aerospace supply webs', *Journal of Operations Management* **20**(6), 691–706. 8

Worall, M., Omer, S. and Riffat, S. B. (2011), 'A hybrid jet-pump CO2 compression system for transport refrigeration', *International Journal of Low-Carbon Technologies* **6**(4), 249–254.
URL: *http://ijlct.oxfordjournals.org/cgi/doi/10.1093/ijlct/ctr011* 64

Wright, T. P. (1936), 'Factors Affecting the Cost of Airplanes', *Journal of the Aeronautical Sciences* **3**(4), 122–128.
URL: *http://arc.aiaa.org/doi/10.2514/8.155* 31

Wynstra, F., Van Weele, A., Weggemann, M., Weele, A. V. and Weggemann, M. (2001), 'Managing Supplier Involvement in Product Development: Three Critical Issues', *European Management Journal* **19**(2), 157–167.
URL: *http://dx.doi.org/10.1016/S0263-2373(00)00090-6* 28

Xu, X., Chen, J.-Q. and Xie, S. Q. (2006), 'Framework of a product lifecycle costing system', *Journal of Computing and Information Science in Engineering* **6**(March 2006), 69–77.
URL: *http://dx.doi.org/10.1115/1.2161227* 22, 37

Zaloom, V. and Miller, C. (1982), 'A review of cost estimating for advanced composite materials applications', *Engineering Costs and Production Economics* **7**(1), 81–86.
URL: *http://dx.doi.org/10.1016/0167-188X(82)90012-X* 12, 23

Zhao, Y. (2012), 'Why 787 Slips Were Inevitable?'. 10

Zhao, Y., Cavusgil, E. and Cavusgil, S. T. (2014), 'An investigation of the black-box supplier integration in new product development', *Journal of Business Research* **67**(6), 1058–1064.
URL: *http://dx.doi.org/10.1016/j.jbusres.2013.06.006* 28

A | Appendix A - Model Formulation

A.1 | Forming Processes

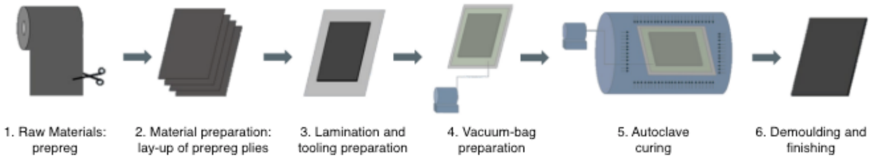

Figure A.1: Traditional Autoclaving (TA) process. Source: Santos (2017).

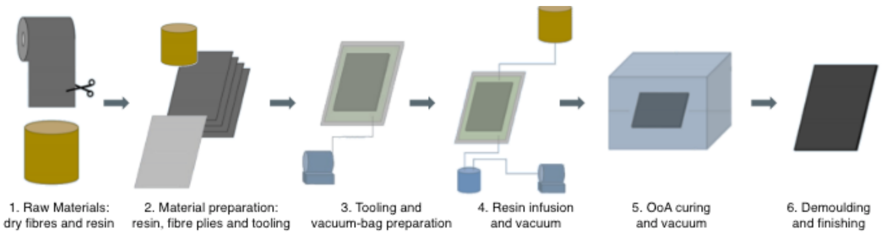

Figure A.2: Vacuum-Assisted Resin Infusion (VARI) process. Source: Santos (2017).

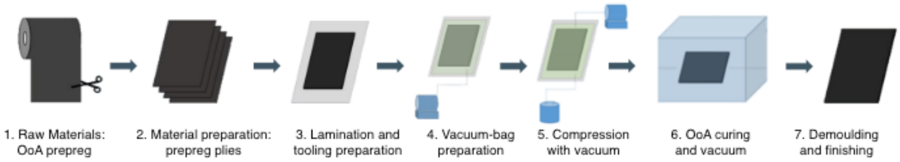

Figure A.3: Vacuum-Bag Only (VBO) process. Source: Santos (2017).

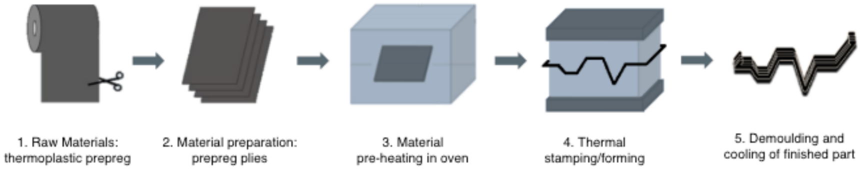

Figure A.4: Thermo-Stamping (TS) process. Source: Santos (2017).

A.2 | Model

A.2.1 | Sets, indexes, parameters and variables

Table A.1: Sets, subsets and indexes

Index		Set	Subsets
i, j	Entities or Locations	L	$= L_{sup} \cup L_f \cup L_w \cup L_c \cup L_{air} \cup L_{port} \cup L_{mtp}$ $= L_{REG1} \cup L_{REG2} \cup L_{REG3}$
i	Focal entity		
j	Third party		
z	Transport modes	Z	$= Z_{truck} \cup Z_{plane} \cup Z_{boat}$ $= Z_{cool} \cup Z_{nocool}$
r	Resources	R	$= R_{tech} \cup R_{labour}$
m	Materials	M	$= M_{raw} \cup M_{support} \cup M_{product}$
p	Products		$p \equiv m \in M_{products}$
t	Period (micro)		
y	Period (macro		
a	Manufacturing activity		
γ		Γ	Type of investments
λ		Λ	Environmental Midpoint Categories
ψ		Ψ	Social impact categories
		Subset	
		L_{sup}	Suppliers
		L_f	Factories
		L_w	Warehouses
		L_c	Customers
		L_{air}	Airports
		L_{port}	Seaports
		L_{mtp}	Material Transfer Points
		L_{REG1}	Entities in Region 1
		L_{REG2}	Entities in Region 2
		L_{REG3}	Entities in Region 3
		Z_{truck}	Truck
		Z_{plane}	plane
		Z_{boat}	boat
		Z_{cool}	Transport with cooling
		Z_{nocool}	Transport without cooling
		Z_{fleet}	Private fleet
		R_{tech}	Production technologies
		R_{labour}	Labour
		M_{raw}	Raw materials
		$M_{support}$	Support materials
		$M_{products}$	Finished products
		M_{mat}	Manufacturing materials
		M_{nocool}	Non-cooled materials
		M_{cool}	Cooled materials
		N	Full network connections
		N_{NET}	Allowed connections
		$N_{OUT_{i/x}}$	Outbound flow
		$N_{IN_{i/x}}$	Inbound flow
		N_{INTRA}	Intra-continental flow
		N_{INTER}	Inter-continental flow

Table A.2: Parameters

Parameter	Description
$batch_{a,p}$	Batch size for activity a in process p
$bigM$	Big enough value
$demand_{i,t}$	Demand of product by customer in location i in period t
$dist_{lo,ld}$	Distance between lo and ld
$driveHrsWk^{max}$	Maximum driving hours per week
$initFleet_{z,i}$	Initial fleet level of mode z at location i
$initRes_{r,i}$	Initial composition of resources r at location i
$initStock_{m,i}$	Initial stock level of material m at location i
$invTruck^{max}$	Maximum investment in trucks
$learningCurve_{r,y}$	Learning curve, alternative to productivity
lot_m	Lot size for material m
$nomWeight_{mat}$	Nominal weight of material mat
$pBOM_{mat,p}$	Bill of materials mat for process p
$pBOT_{r,p,a}$	Bill of resources r for process p in activity a
$prod_r$	Productivity of resource r
$prodArea_m$	Area occupied by material/product m
$prodWeight_m$	Weight of material/product m
$pTOP_{a,p}$	Duration of activity a for process p
$rejRate$	Rejection rate for finished parts with quality issues
$scaleUp_{a,p}$	Time scale-up factor for activity a in process p
$scaleUpMult$	Scale-up multiplier based on area from testbed
$supCapacity_i$	Max capacity of supplier i
$t_{h/shift}$	Number of hours per shift
$t_{shifts/d}$	Number of shifts per day
$t_{ds/mth}$	Number of working days per month
$t_{mths/yr}$	Number of month in a year
$tAcquire_z$	Cost of acquiring mean z
$tCap_z^{min}$	Minimum capacity of transportation mode z per time period
$tCapMat_z^{max}$	Material capacity of transportation mode z in weight per time period
$tCapProd_z^{max}$	Product capacity of transportation mode z in units per time period
$tCont_z^{max}$	Annual maximum number of trips contracted for mode z
$trAvgS$	Truck average speed
$wkTimePeriod$	Number of weeks per time period (month)

A.2.2 | Constraints

Demand

$$\sum_{m \in M_{products}} \sum_{j \in F_{IN_{c/fp}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} = \sum_t demand_{i,t} \cdot \frac{1}{(1 - rejRate)} \quad , \forall\, y, \forall\, (i \in L_c) \tag{A.1}$$

Manufacturing

$$\sum_a pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot \frac{1}{batch_{a,p}} \cdot scaleUp_{a,p} \cdot P_{i,p,y} \leqslant prod_r \cdot R_{r,i,y} \cdot t_{h/shift} \cdot t_{shifts/d} \cdot t_{ds/mth} \cdot t_{mths/yr}$$

$$, \forall\, i, p, r, y \tag{A.2}$$

$$\sum_y P_{i,p,y} \leqslant bigM \cdot \Omega_p \quad , \forall\, (i \in L_f), \forall\, p \tag{A.3}$$

$$\sum_p \Omega_p = 1 \tag{A.4}$$

Table A.3: Decision Variables

Continuous variables:	
$F_{z,i,y}$	Fleet composition (trucks z owned) and assigned to i in period y
$P_{i,p,y}$	Production of p in location i in period y
$PO_{i,j,m,y}$	Material m ordered from i to j (purchase order) in period y
$R_{r,i,y}$	Amount of resources r hired/owned for location i in period y
$S_{i,m,y}$	Amount of inventory (stock) of m in i in period y
$T_{z,i,j,y}$	Number of trips of mode z from i to j in period y
$Tr^{period}_{z,i,y}$	Trucks z owned and assigned to i in period y
$X_{i,j,m,z,y}$	Outbound flow of material m from i to j using mode z in period y
$X_{j,i,m,z,y}$	Inbound flow of material m to i from j using mode z in period y
Binary variables:	
Θ_i	1, if entity in location i is open; 0, otherwise
$\zeta_{z,y}$	1, if transportation mode z is used in period y; 0, otherwise
Ω_p	1, if forming process for product p is selected; 0, otherwise
Integer variables:	
$AddR_{r,i,y}$	Amount of resources r hired/bought for location i in period y
$CutR_{r,i,y}$	Amount of resources r fired/sold for location i in period y
$BuyT_{z,i,y}$	Trucks z bough and assigned to i in period y
$SellT_{z,i,y}$	Trucks z assigned to i sold in period y
$CellsOpen_{i,y}$	Amount of cells open at location i in period y

Table A.4: Variables for Objective Functions

Economic Auxiliary variables:	
DC_y	Depreciation rate for period y
FCI_γ	Fixed capital investment per γ
NE_y	Net earnings in period y
CF_y	Cash flow for period y
NPV	Net present value

Resources

$$initRes_{r,i} + AddR_{r,i,y} - CutR_{r,i,y} = R_{r,i,y} \quad ,\forall\, r,i,\forall\,\{y \in Y : y = 1\} \tag{A.5}$$

$$R_{r,i,y-1} + AddR_{r,i,y} - CutR_{r,i,y} = R_{r,i,y} \quad ,\forall\, r,i,\forall\,\{y \in Y : y > 1\} \tag{A.6}$$

Material Balance

Warehouses

$$initStock_{m,i} + \sum_{j \in F_{IN_{wh/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} = S_{i,m,y} + \sum_{j \in F_{OUT_{wh/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \quad ,\forall\, m, \forall\,\{y \in Y : y = 1\}, \forall\,(i \in L_w) \tag{A.7}$$

$$S_{i,m,y-1} + \sum_{j \in F_{IN_{wh/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} = S_{i,m,y} + \sum_{j \in F_{OUT_{wh/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \quad ,\forall\, m, \forall\,\{y \in Y : y > 1\}, \forall\,(i \in L_w) \tag{A.8}$$

Table A.5: Parameters for Objective Functions

Economic Parameters:	
$annualRevenue_y$	Revenue in year y
avC_z	Average fuel consumption of mode z
$cContract_z$	Cost of contract w/ carrier for mode z
$cellC_{m,i}$	Install cell for material m at i
$discRt$	Discount rate
$firingC_r$	Cost of firing/selling resource r
fp	Fuel price
$hiringC_r$	Cost of hiring/buying resource r
$holdC_m$	Holding cost of material m
$hubVarC_i$	Variable cost at hub i
$inv_i^{facility}$	Investment cost for facility at location i
inv_i^{others}	Other investments at location i
inv_r^{equip}	Investment in technology r
$inv_p^{tooling}$	Investment in tooling for process p
inv_z^{truck}	Investment in trucks z
$kmRt$	Rate per kilometer
$matP_{m,i}$	Price of material m from supplier i
$resRt_r$	Rate of resource r per time unit
sv_γ	Salvage value of investment γ
$taxRt$	Tax rate
$tripRt_z$	Rate per trip for mode z
$vhcMntc_z$	Maintenance of mode z
Environmental Parameters:	
$matFootprint_{\lambda,m,i}^{supplier}$	Environmental impact (per λ) per unit of raw material m consumed from supplier i
$envFact_{\lambda,r}^{res}$	Environmental impact (per category λ) per hour of using resource r
$envFact_{\lambda,z}^{transp}$	Environmental impact (per category λ) per kg.km transported by mode z
$envFact_{\lambda,m}^{storage}$	Environmental impact (per category λ) per unit of material m stored
$envFact_{\lambda,i}^{entity}$	Environmental impact (per category λ) of installing facilities at location i
Social Parameters:	
$matSocFootprint_{\psi,m,i}^{supplier}$	Social impact (per ψ) per unit of raw material m consumed from supplier i
$socFact_{\psi,p}^{manuf}$	Social impact (per category ψ) per unit of product p produced
$socFact_{\psi,z}^{transp}$	Social impact (per category ψ) per trip using mode z
$socFact_{\psi,m}^{storage} \cdot \Theta_i$	Social impact (per category ψ) per unit of material m stored
$socFact_{\psi,i}^{entity}$	Social impact (per category ψ) of installing facilities at location i

Factories

$$initStock_{p,i} + P_{i,p,y} = S_{i,p,y} + \sum_{j \in F_{OUT_{f/fp}}} \sum_{z \in N_{NET}} X_{i,j,p,z,y}$$

$$, \forall\, p, \forall\, (i \in L_f), \forall\, \{y \in Y : y = 1\} \tag{A.9}$$

$$S_{i,p,y-1} + P_{i,p,y} = S_{i,p,y} + \sum_{j \in F_{OUT_{f/fp}}} \sum_{z \in N_{NET}} X_{i,j,p,z,y}$$

$$, \forall\, p, \forall\, (i \in L_f), \forall\, \{y \in Y : y > 1\} \tag{A.10}$$

$$
\begin{aligned}
initStock_{m,i} + \sum_{j \in F_{IN_{f/rm}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y-1} = S_{i,m,y} \\
+ \sum_{p} \sum_{j \in F_{OUT_{wh/fp}}} \sum_{z \in N_{NET}} pBOM_{m,p} \cdot scaleUpMult \cdot P_{i,m,y} \\
, \forall \, (m \in M_{mat}), \forall \, (i \in L_f), \forall \, \{y \in Y : y = 1\}
\end{aligned} \tag{A.11}
$$

$$
\begin{aligned}
S_{i,m,y-1} + \sum_{j \in F_{IN_{f/rm}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y-1} = S_{i,m,y} \\
+ \sum_{p} \sum_{j \in F_{OUT_{wh/fp}}} \sum_{z \in N_{NET}} pBOM_{m,p} \cdot scaleUpMult \cdot P_{i,m,y} \\
, \forall \, (m \in M_{mat}), \forall \, (i \in L_f), \forall \, \{y \in Y : y > 1\}
\end{aligned} \tag{A.12}
$$

$$
\sum_{z \in N_{NET}} X_{i,j,m,z,y} = lot_m \cdot PO_{i,j,m,y} \qquad , \forall \, (m \in M_{mat}), \forall \, i, j, y \tag{A.13}
$$

Cross-docking at Airports and Seaports

$$
\sum_{j \in F_{IN_{air/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} = \sum_{j \in F_{OUT_{air/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \qquad , \forall \, m, \forall \, (i \in L_{air}), \forall \, y \tag{A.14}
$$

$$
\sum_{j \in F_{IN_{port/x}}} \sum_{z \in N_{NET}} X_{j,i,m,z,y} = \sum_{j \in F_{OUT_{port/x}}} \sum_{z \in N_{NET}} X_{i,j,m,z,y} \qquad , \forall \, m, \forall \, (i \in L_{port}), \forall \, y \tag{A.15}
$$

Storage

$$
\sum_{m \in M_{mat}} nomWeight_m \cdot S_{i,m,y} \leqslant cellCap_{m,i} \cdot CellsOpen_{i,y} \qquad , \forall \, [i \in (L_w \cup L_f)], \forall \, y \tag{A.16}
$$

$$
\sum_{m \in M_{product}} S_{i,m,y} \leqslant cellCap_{m,w} \cdot CellsOpen_{i,y} \qquad , \forall \, [i \in (L_w \cup L_f)], \forall \, y \tag{A.17}
$$

$$
\sum_{m} nomArea_m \cdot S_{i,m,y} \leqslant cellAreaCap_{m,i} \cdot CellsOpen_{i,y} \qquad , \forall \, [i \in (L_w \cup L_f)], \forall \, y \tag{A.18}
$$

$$
\sum_{i,y} CellsOpen_{i,y} \leqslant bigM \cdot \mathit{\Theta}_i \qquad , \forall \, [i \in (L_w \cup L_f)], \forall \, y \tag{A.19}
$$

Transportation

Capacities of modes

$$
\begin{aligned}
tCapMat_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{m \in (M_{mat} \cap N_{NET})} nomWeight_m \cdot X_{i,j,m,z,y} \\
, \forall \, (z \in Z_{truck}), \forall \, [(i,j) \in N_{ALL}], \forall \, y
\end{aligned} \tag{A.20}
$$

$$
\begin{aligned}
tCapProd_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{p \in N_{NET}} X_{i,j,p,z,y} \\
, \forall \, (z \in Z_{truck}), \forall \, [(i,j) \in N_{ALL}], \forall \, y
\end{aligned} \tag{A.21}
$$

$$
\begin{aligned}
tCap_z^{min} \cdot T_{z,i,j,y} \leqslant \sum_{m \in N_{NET}} X_{i,j,m,z,y} \\
, \forall \, (z \in Z_{truck}), \forall \, [(i,j) \in N_{ALL}], \forall \, y
\end{aligned} \tag{A.22}
$$

$$tCapMat_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{m \in (M_{mat} \cap N_{NET})} nomWeight_m \cdot X_{i,j,m,z,y}$$

$$, \forall\, [z \in (Z_{boat} \cup Z_{plane})], \forall\, [(i,j) \in N_{ALL}], \forall\, y \tag{A.23}$$

$$tCapProd_z^{max} \cdot T_{z,i,j,y} \geqslant \sum_{p \in N_{NET}} X_{i,j,p,z,y}$$

$$, \forall\, [z \in (Z_{boat} \cup Z_{plane})], \forall\, [(i,j) \in N_{ALL}], \forall\, y \tag{A.24}$$

$$tCap_z^{min} \cdot T_{z,i,j,y} \leqslant \sum_{m \in N_{NET}} X_{i,j,m,z,y}$$

$$, \forall\, [z \in (Z_{boat} \cup Z_{plane})], \forall\, [(i,j) \in N_{ALL}], \forall\, y \tag{A.25}$$

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y} \quad , \forall\, [z \in (Z_{boat} \cup Z_{plane})], \forall\, [(i,j) \in N_{ALL}], \forall\, y \tag{A.26}$$

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y} \quad , \forall\, (z \in Z_{truck}), \forall\, [(i,j) \in N_{ALL}], \forall\, y \tag{A.27}$$

Fleet

$$initFleet_{z,i} + BuyT_{z,i,y} - SellT_{z,i,y} = F_{z,i,y}, \forall\, z, i, \forall\, \{y \in Y : y = 1\} \tag{A.28}$$

$$F_{z,i,y-1} + BuyT_{z,i,y} - SellT_{z,i,y} = F_{z,i,y}, \forall\, z, i, \forall\, \{y \in Y : y > 1\} \tag{A.29}$$

$$Tr_{z,i,y}^{period} = \frac{\sum_{j \in N_{intra}} (2 \cdot dist_{i,j} \cdot T_{z,i,j,y})}{v^{avg} \cdot driveHrsWk^{max} \cdot wkTimePeriod} \quad , \forall\, (z \in Z_{truck}), \forall\, i, y \tag{A.30}$$

$$F_{z,i,y} \geqslant Tr_{z,i,y}^{period} \quad , \forall\, (z \in Z_{truck}), \forall\, i, y \tag{A.31}$$

$$\sum_{z,i} tAcquire_z \cdot BuyT_{z,i,y} \leqslant invTruck^{max} \quad , \forall\, y \tag{A.32}$$

$$\tag{A.33}$$

Physical constraints

$$\sum_{\substack{j \in N_{NET} \\ j \notin L_{air}}} \sum_{z \notin Z_{plane}} X_{j,i,m,z,y} = \sum_{\substack{j \in N_{NET} \\ j \in L_{air}}} \sum_{z \in Z_{plane}} X_{i,j,m,z,y} \quad , \forall\, m, \forall\, (i \in L_{air}), \forall\, y \tag{A.34}$$

$$\sum_{\substack{j \in N_{NET} \\ j \notin L_{port}}} \sum_{z \notin Z_{boat}} X_{j,i,m,z,y} = \sum_{\substack{j \in N_{NET} \\ j \in L_{port}}} \sum_{z \in Z_{boat}} X_{i,j,m,z,y} \quad , \forall\, m, \forall\, (i \in L_{port}), \forall\, y \tag{A.35}$$

$$\tag{A.36}$$

Capacities of Entities

$$\sum_j PO_{i,j,m,y} \leqslant supCapacity_i \cdot \Theta_i, \forall\, (m \in M_{mat}), \forall\, (i \in L_{sup}), \forall\, y \tag{A.37}$$

$$\sum_{(m,z,j) \in N_{NET}} X_{j,i,m,z,y} \leqslant bigM \cdot \Theta_i, \forall\, (i \notin L_{sup}), \forall\, y \tag{A.38}$$

$$\sum_{(m,z,i) \in N_{NET}} X_{i,j,m,z,y} \leqslant bigM \cdot \Theta_j, \forall\, (j \notin L_{sup}), \forall\, y \tag{A.39}$$

A.2.3 | Objective Functions

Economic Objective Function

$$\textit{maximise} \qquad NPV = \sum_{y} \left(\frac{CF_y}{(1+discRt)^{(y)}} \right) - \sum_{\gamma} FCI_\gamma \tag{A.40}$$

$$FCI_\gamma = \begin{cases} \displaystyle\sum_{i \in L_f \cup L_w} (inv_i^{facility} + inv_i^{others}) \cdot \mathit{\Theta}_i, \quad \gamma = 1 \\ \displaystyle\sum_{p} \Big[\sum_{\substack{y \\ m \\ r \in R_{tech}}} (inv_r^{equip} \cdot AddR_{r,i,y}) \\ +(inv_p^{tooling} \cdot \mathit{\Omega}_p)\Big], \quad \gamma = 2 \\ \displaystyle\sum_{z \in Z_{fleet}} \sum_{i} inv_z^{truck} \cdot BuyT_{z,i,y}, \quad \gamma = 3 \end{cases} \tag{A.41}$$

Where $\gamma = 1$ represents the facilities and related investments, $\gamma = 2$ is for the equipment and $\gamma = 3$ is for the tangible assets (trucks)

$$CF_y = \begin{cases} NE_y & , \ t = 1, \ldots, NT-1 \\ NE_y + \displaystyle\sum_{\gamma} (sv_\gamma \cdot FCI_\gamma) & , \ t = NT \end{cases} \tag{A.42}$$

NT is the last period

$$DC_y = \sum_{\gamma} DP_{\gamma,y} \cdot FCI_\gamma \tag{A.43}$$

$$\begin{aligned} NE_y = (1 - taxRt) \cdot \Bigg[& annualRevenue_y - \sum_{y} \Big[\sum_{m,i,j} (matP_{m,i} \cdot lot_m \cdot PO_{i,j,m,y}) \\ & + \sum_{\substack{i \\ r \in R_{labour}}} [(firingC_r \cdot CutR_{r,i,y} + hiringC_r \cdot AddR_{r,i,y}) + (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y})] + \\ & \sum_{\substack{i \\ r \in R_{tech}}} (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y}) + \sum_{i,j,m} (\sum_{z} (cContract_z \cdot \zeta_{z,y})) \\ & + \sum_{z \in Z_{truck}} ((\frac{avC_z}{100} \cdot fp + vhcMntc_z) \cdot 2 \cdot dist_{i,j} \cdot T_{z,i,j,y}) + \sum_{z \in Z_{plane} \cup Z_{boat}} ((tripRt_z + kmRt \cdot dist_{i,j}) \cdot T_{z,i,j,y}) \\ & + \sum_{j,i \in L_{mtp}} (hubVarC_i \cdot (X_{i,j,m,z,y} + X_{j,i,m,z,y})) + \sum_{i,m} (cellC_{m,i} \cdot CellsOpen_{i,y} + holdC_m \cdot S_{i,m,y}) \Big] \Bigg] \\ & + \Big(taxRt \cdot DC_y \Big) \end{aligned} \tag{A.44}$$

Environmental Objective Function

minimise
$$EnvImpact = \sum_{\substack{\lambda \\ y}} normF_{\lambda} \cdot \left[\sum_{\substack{p \\ a \\ i \in L_f}} (envFact^{res}_{\lambda,r} \cdot pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot P_{i,p,y}) \right.$$
$$+ \sum_{m} \sum_{(i,j)} (matFootprint^{supplier}_{\lambda,m,i} \cdot lot_m \cdot PO_{i,j,m,y})$$
$$+ \sum_{\substack{z \\ (m,i,j) \in N_{NET}}} (envFact^{transp}_{\lambda,z} \cdot nomWeight_m \cdot dist_{i,j} \cdot X_{i,j,m,z,y})$$
$$\left. + \sum_{\substack{m \\ i \in (L_f \cup L_w)}} (envFact^{storage}_{\lambda,m} \cdot S_{i,m,y}) + \sum_{i \in (L_f \cup L_w)} (envFact^{entity}_{\lambda,i} \cdot \Theta_i) \right] \tag{A.45}$$

Social Objective Function

minimise $SocImpact$
$$= \sum_{\psi} \sum_{y} normF_{\psi} \cdot \left[\sum_{p,a} \sum_{i \in L_f} (socFact^{manuf}_{\psi,p} \cdot P_{i,p,y}) + \sum_{m} \sum_{(i,j)} (matSocFootprint^{supplier}_{\psi,m,i} \cdot lot_m \cdot PO_{i,j,m,y}) \right.$$
$$\left. + \sum_{(m,i,j) \in N_{NET}} \sum_{z} (socFact^{transp}_{\psi,z} \cdot T_{z,i,j,y}) + \sum_{m} \sum_{i \in (L_f \cup L_w)} (socFact^{storage}_{\psi,m} \cdot S_{i,m,y}) + \sum_{i \in (L_f \cup L_w)} (socFact^{entity}_{\psi,i} \cdot \Theta_i) \right] \tag{A.46}$$

B | Appendix B - Case Study

B.1 | Materials

Table B.1: Materials social impact.

Material	Description	Social impact
$rm1$	1 lot, prepreg, HexPly M21	0.000001
$rm2$	1 lot, fibre, HiTape HexTow AS7	0.000001
$rm3$	1 lot, resin, HexFlow RTM6-2	0.0000001
$rm4$	1 lot, prepreg, HexPly M56	0.000001
$rm5$	1 lot, prepreg, Thermoplastic Prepreg APC-2-PEEK	0.000001

B.2 | Manufacturing

Table B.2: Technology needs per product. Source: Santos (2017)

	Resource	P1	P2	P3	P4
$o1$	Autoclave	Yes	No	No	No
$o2$	Oven	No	Yes	Yes	Yes
$o3$	Press	No	No	No	Yes
$o4$	Vacuum	Yes	Yes	Yes	No
$l1$	Labour	Yes	Yes	Yes	Yes

Table B.3: Product weight. Source: Marques (2018)

Product	Material	Density ($kg.m^3$)	Part Volume (m^3)	Percent Volume (%)	Part weight (kg)
$P1$	$rm1$	1580	0.36	100	568.80
$P2$	$rm2$	1790	0.36	60	546.48
$P2$	$rm3$	1110	0.36	40	
$P3$	$rm4$	1530	0.36	100	550.80
$P4$	$rm5$	1320	0.36	100	475.20

B.3 | Transportation

Table B.4: Transportation modes

Description	Capacity (ton)	Prod. Capacity (units)	Materials	Max. Trips
Regular truck	25	-	1, 5	3000
Truck w/ cold	25	-	1, 2, 3, 4, 5	3000
Large truck	40	4	2, 5, FP	3000
Large truck w/ cold	40	4	1, 2, 3, 4, 5, FP	3000
Cargo plane	137.75	20	2, 5, FP	100
Plane w/ cold	137.75	20	1, 2, 3, 4, 5, FP	100
Cargo ship	49900	80	2, 5, FP	100
Ship w/ cold	49900	80	1, 2, 3, 4, 5, FP	100

Table B.5: Environmental impact for truck

Option	Source	Reference	kg CO^2 eq.
		Regular freight truck (25ton)	
1	SimaPro®	1 $kg.km$ Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000091521
2	SimaPro®	1 $kg.km$ Transport, freight, lorry, unspecified {GLO}| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000134519
3	LIPASTO	1 $kg.km$ Transport, Semi trailer combination, EURO6 , Gross vehicle mass 40t, pay load capacity 25t, fully loaded, Highway driving	0.000035000
-		**Average value**	**0.00011302**
		Refrigerated freight truck (25ton)	
1	SimaPro®	1 $kg.km$ Transport, freight, lorry with reefer, cooling {GLO} | market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000129751
2	SimaPro®	1 $kg.km$ Transport, freight, lorry with reefer, freezing {GLO}| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000128146
3	SimaPro®	1 $kg.km$ Transport, freight, lorry with refrigeration machine, cooling {GLO}| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0000443212
4	SimaPro®	1 $kg.km$ Transport, freight, lorry with refrigeration machine, freezing GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000443212
-		**Average value**	**0.00028608**
		Special truck (40ton)	
1	LIPASTO	1 $kg.km$ Transport, Full trailer combination, EURO6 , Gross vehicle mass 60t, pay load capacity 40t, fully loaded, Highway driving	0.000030000
-		**Average value**	**0.000030000**
		Special refrigerated truck (40ton)	
1	Inferred*	1 $kg.km$ Transport, Full trailer combination, EURO6 , Gross vehicle mass 60t, pay load capacity 40t, fully loaded, Highway driving	0.000075937
-		**Average value**	**0.000075937**

* Derived from regular freight truck (25ton), using a relation of 253%.

Table B.6: Environmental impact for plane

Option	Source	Reference	kg CO^2 eq.
		Regular cargo plane	
1	SimaPro®	1 $kg.km$ Transport, freight, aircraft GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.001172995
2	LIPASTO	1 $kg.km$ Transport, Average freight air transport emissions and energy consumption, Short-haul international flights	0.001416
3	LIPASTO	1 $kg.km$ Transport, Average freight air transport emissions and energy consumption, Long-haul international flights	0.000600
-		**Average value**	**0.001062998**
		Refrigerated cargo plane	
1	SimaPro®	1 $kg.km$ Transport, freight, aircraft with reefer, cooling GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.001173586
2	SimaPro®	1 $kg.km$ Transport, freight, aircraft with reefer, freezing GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.001173442
-		**Average value**	**0.001173514**

Table B.7: Environmental impact for ship

Option	Source	Reference	kg CO^2 eq.
		Regular cargo ship	
1	SimaPro®	1 $kg.km$ Transport, freight, sea, transoceanic tanker GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000004700
2	SimaPro®	1 $kg.km$ Transport, freight, sea, liquefied natural gas GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000023720
3	SimaPro®	1 $kg.km$ Transport, freight, sea, transoceanic ship GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0,000011773
4	LIPASTO	1 $kg.km$ Transport, freight, Container ship, 1 000 TEU	0.000042
5	LIPASTO	1 $kg.km$ Transport, freight, Container ship, 2 000 TEU	0.000028
6	LIPASTO	1 $kg.km$ Transport, freight, general cargo ship, small	0.000028
7	LIPASTO	1 $kg.km$ Transport, freight, general cargo ship, Multi purpose carrier	0.000029
-		**Average value**	**0.000023885**
		Refrigerated cargo ship	
1	SimaPro®	1 $kg.km$ Transport, freight, inland waterways, barge with reefer, cooling GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000065838
2	SimaPro®	1 $kg.km$ Transport, freight, inland waterways, barge with reefer, freezing GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000062228
3	SimaPro®	1 $kg.km$ Transport, freight, sea, transoceanic ship with reefer, cooling GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000023147
4	SimaPro®	1 $kg.km$ Transport, freight, sea, transoceanic ship with reefer, freezing GLO| market for | Conseq, S (of project Ecoinvent 3 - consequential - system)	0.000020369
-		**Average value**	**0.000042895**

Table B.8: Transportation social impact per kg.km.

Mode	Social impact
Truck	0.000000001
Plane	0.000000001
Boat	0.000000001

Table B.9: Distance matrix

	$i1$	$i2$	$f1$	$j1$	$airUS$	$airPT$	$airBR$	$airFR$	$portUS$	$portPT$	$portBR$	$portFR$
$i1$	-	09480	01655	09251	09500	01726	09251	00024	09500	01813	09251	00327
$i2$	-	-	09419	09916	00025	09125	09916	09473	00042	09196	09916	09664
$f1$	-	-	-	07938	09243	00134	07938	01627	09243	00170	07938	01553
$j1$	-	-	-	-	09907	07910	00030	09240	09510	07834	00112	09057
$airUS$	-	-	-	-	-	09119	09895	09491	00063	09199	09987	09669
$airPT$	-	-	-	-	-	-	07884	01400	09149	00159	07921	01607
$airBR$	-	-	-	-	-	-	-	09230	09935	07834	00111	09258
$airFR$	-	-	-	-	-	-	-	-	09494	01789	09258	00302
$portUS$	-	-	-	-	-	-	-	-	-	13320	13681	14804
$portPT$	-	-	-	-	-	-	-	-	-	-	08130	01805
$portBR$	-	-	-	-	-	-	-	-	-	-	-	09380
$portFR$	-	-	-	-	-	-	-	-	-	-	-	-

C | Appendix C - Results

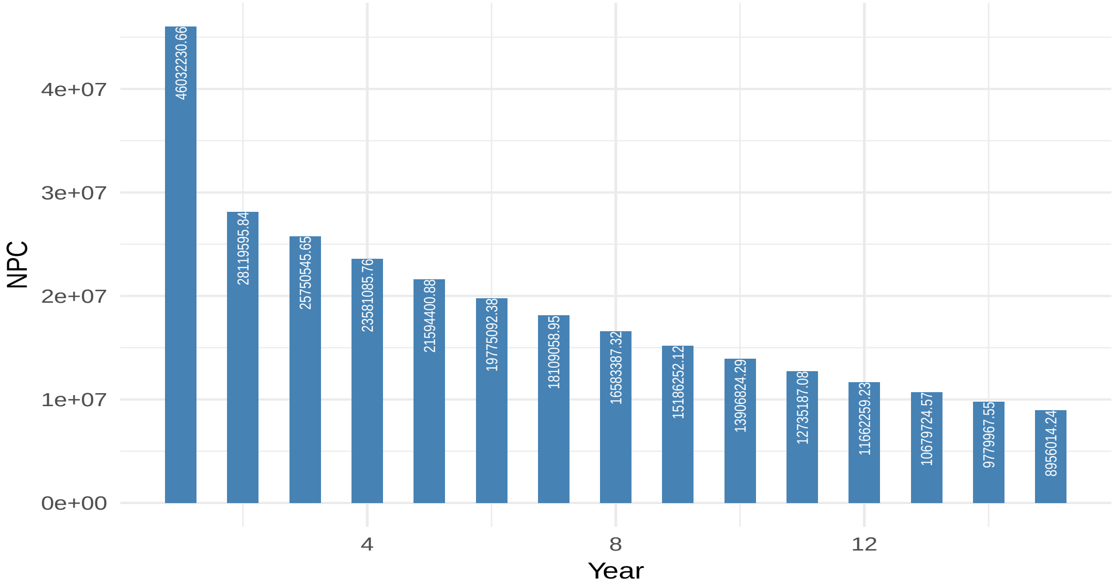

Figure C.1: Net Present Cost (NPC) for each period (€).

Table C.1: Resource needs for each scale-up factor

		Time scale-up factor							
Process	Resource	1	2	3	4	5	6	7	8
TA	Autoclave	1	2	2	3	3	4	5	5
	Vacuum	1	2	2	3	3	4	5	5
	Labour	1	1	1	1	1	1	2	2
VARI	Oven	1	2	2	3	3	4	5	5
	Vacuum	1	2	2	3	3	4	4	5
	Labour	1	1	2	2	3	3	4	4
VBO	Oven	1	2	3	4	5	6	6	7
	Vacuum	1	2	3	4	5	6	7	8
	Labour	1	1	1	1	1	2	2	2

Table C.2: Computational Results

	Economic	Environmental	Social
Variables	30,598	30,598	30,598
Discrete Variables	5,543	5,543	5,543
Constraints	21,399	21,399	21,399
Iterations used	7,965	782	791
Relative Gap	0.00	0.00	0.00
Time to solve algorithm (s)	1,893.74	388.34	375.96