Towards the conception of a Supply Chain efficient and sustainable in the Aeronautic industry - Airbus case study

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Vers la conception d'une Supply Chain entrante efficiente et durable dans l'industrie aéronautique

Etude de Cas chez Airbus

Towards the conception of an efficient and sustainable inbound supply chain in the aeronautic industry

Airbus Case Study

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Table of Contents

List of tables

List of Figures

Introduction

In this thesis, we will develop modelling and optimization tools that support inbound Supply Chain Network Design (SCND) for industries with small production rates, bulky and expensive products and a constrained network configuration.

We will use the tools developed in an example of the aeronautic industry, and more particularly, the helicopters industry. The helicopters supply chain is characterized by very small production rates (Ex: 30 helicopters per year for a type of helicopter) compared to other industries as the automotive industry for example. In this study, we focus on inbound SCND. Due to small production volumes, helicopters manufacturers are often in a weak position in relation to their suppliers (they represent an insignificant part of the turnover of their suppliers). This results on an inbound supply chain network configuration that is difficult to modify. Moreover, in several cases, in the aeronautic industry, transportation is managed by suppliers (Roy and Elias, 2018), and there is no visibility over transportation operations and costs. This results on an inbound supply chain that is not optimized as a whole. Given that there is no visibility over transportation costs, procurement policies are defined only in function of storage costs, without considering transportation costs. Taking into account these characteristics, the objective of this Ph.D. is to develop optimization and modelling tools that support inbound SCND by minimizing total cost and reducing CO_2 emissions in the aeronautic industry or industries with the same characteristics (*i.e.* construction and mining equipment industry, tailor-made products) and that allow providing managerial insights for optimizing inbound supply chain in these industries.

Airbus Transformation Plan Context

Airbus Helicopters (AH) is a division of Airbus, a worldwide leader in the aerospace industry (see Annex 1 for more details) and the first helicopter manufacturer (Airbus, 2020). The helicopters market is currently in the maturity stage of its product life cycle. The transport offshore, one of the most promising sectors, has been being reduced during the last years. The oil price reduction and oil market uncertainty forces the oil companies to slow down their development projects. The transport offshore helicopters are part of civil range products in AH, which represents 45% of the market.

Within this maturity stage, competitiveness is essential for Airbus in order to maintain its market position. Hence Airbus has adopted a strategy which prioritizes cost reduction and production efficiency improvement. This strategy has taken the form of a transformation plan.

The objective of the transformation plan is to improve industrialization methods including production and logistics design process. It has been structured around four priorities: 1) Customer Satisfaction, 2) Security and Quality, 3) Product competitiveness and innovation and 4) Focus on People.

The H160 Helicopter is the first of a new generation that started with the transformation plan. It integrates several technological advances that place it as the leader light-heavy helicopters line. Airbus Helicopters considers that the real achievement concerns the H160 industrialization: it was developed for the industry and not for technical feats. The modularity concept was incorporated in its design, allowing the production system to be more efficient and performant (Figure 0.1). As an example, the assembly time of a helicopter has been divided by two; it passed from 90 days to 40 days. In this new production system, different modules are produced at different Airbus sites. This has modified also procurement policies.

The launching of this new range of products has been the occasion to implement industrialization processes and to launch different production and logistics optimization projects.

Figure 0.1. Modularization program

Inbound Supply Chain Optimization

Within the transformation context presented previously, AH decided to launch a project in order to optimize its current inbound supply chain. Currently inbound transportation is managed by suppliers in 80% of the cases and there is no visibility over transportation costs and operations, as it is the case in several companies in the aeronautic industry (Roy and Elias, 2018). This results in a current inbound supply chain that is not optimized as a whole. For this reason, Airbus decided to launch a research project with the aim of developing modeling and optimization tools that allow supporting the design of an efficient and sustainable inbound supply chain. With this project, Airbus expected to **demonstrate that it was possible to reduce at least by 15% the inbound supply chain logistics costs by optimizing it.** This objective and the decision of launching this project were defined based on some preliminary analysis conducted by the Airbus.

Industrial Project Organization

This project was launched by the industrialization methods team. This team is in charge of the development of industrialization tools in order to improve the efficiency and reduce the costs of the industry. As part of this team, during this thesis I developed modeling and optimization tools mainly for the inbound logistics department. At each stage of the project results obtained and hypothesis were validated by this department. Results obtained in this study were used in order to trigger an inbound logistics transformation project. Hence, during this thesis I worked in close collaboration with all the concerned departments: logistics department, transportation department and purchasing department (which negotiates transportation contracts with suppliers).

Objective

Taking into account the AH inbound supply chain transformation project, the aeronautic supply chain characteristics, and the objective of this Ph.D., we conduct a case study at AH. As it was mentioned previously, the objective of this study is to develop optimization and modelling tools that support inbound Supply Chain Network Design (SCND) by minimizing total cost and reducing CO_2 emissions in the aeronautic industry and similar industries. By using these tools in the AH case, we aim to define a set of guidelines to reduce logistics costs and CO_2 emissions at AH and in general in the aeronautic industry or others industries with the same characteristics. We propose a step-by-step approach in order optimize inbound SCND. In an industrial context, supply chain transformations are costly from an economic and a managerial point of view. With our approach, the supply chain decision makers are able to analyze the implementation effort of each step compared to its benefit. In this way, we provide a very practical and affordable path to transform.

Hereafter we present the main characteristics of the supply chain addressed in this study:

- **Bulky and expensive final products:** In the supply chain addressed final products are bulky and expensive.
- **Small production rates**: The supply chain addressed is characterized by having small production rates. As a consequence, manufacturers are in a position of weakness in relation to their suppliers given that they represent a small part of the turnover of their suppliers. This results in a constrained network configuration that is difficult to modify.
- **Transportation management:** In the supply chain addressed suppliers manage transportation and there is no visibility over transportation operations and costs. This results on an inbound supply chain that is not optimized as a whole. Moreover given that there is no visibility over transportation costs, procurement policies take into account mainly storage costs, without considering transportation costs.
- **Environmental thinking:** In the supply chain addressed the environmental thinking is not integrated in supply chain management.

Taking into account these characteristics, the optimization and modelling tools developed in this study can be applied to supply chains with similar characteristics.

The implementation of inbound supply chain optimization strategies requires modifying the current transportation organization. This is a huge work because all the suppliers' contracts need to be renegotiated. Nevertheless, based on inbound supply chain optimization benefits, we will show the interest of doing this modification.

This PhD report consisting on 6 chapters is organized as follows:

1. **Chapter 1 – Supply Chain Network Design - Literature Review:** In this chapter, we present a literature review conducted on supply chain network design (SCND) area. Particularly we present SCND models classification in function of supply chain management paradigms and decision levels included. At the end of this chapter, we present some SCND case studies and we describe the AH SCND case. We also show the research gap that motivated this study.

2. **Chapter 2 – Current Airbus Supply Chain:** In this chapter, we define the perimeter of the study and we characterize the current AH supply chain. This characterization allows identifying the optimization axes studied in Chapters 3, 4, 5 and 6 and extending them to supply chains with similar characteristics.

3. **Chapter 3 - Transportation Lot Sizing and Mode Selection:** Transportation lot sizing and transportation mode selection are the two first optimization axes identified in the AH case. These optimization axes are characterized by the fact that no network modification is required. In other words, no location decision is evaluated. In this

chapter, we present optimization models developed for each one of these axes and potential benefits.

4. **Chapter 4 – Cross Docks Location and Milk Run Concept Evaluation:** In this chapter, we study cross-dock location optimization axis and milk run implementation around cross-dock facilities. We develop different optimization models per axis and we test them on the AH case. These optimization axes are characterized by requiring network modification with the location of cross-docking facilities.

5. **Chapter 5 – How to Build an Optimized Inbound Supply Chain Network:** In this section, we combine the optimization axes identified in Chapters 3 and 4 in order to design an efficient supply chain at AH. Main driver in this section is cost reduction.

6. **Chapter 6 – How to Build a Sustainable Inbound Supply Chain Network:** In this section, we integrate the sustainability dimension explicitly in our cross-dock location model defining CO_2 emissions constraints. Using this model, we develop a sustainable inbound supply chain solution for AH considering alternative transportation modes and suppliers relocation strategies. Finally, we describe briefly electric road transportation and drones delivery solutions, and their potential benefits for AH.

1. Supply Chain Network Design - Literature Review

A Supply Chain is defined as a "network of business entities connected through upstream and downstream links, involved in different business processes and activities in order to deliver value to customers either in form of physical goods, services or both" (Samaranayake, 2005). In a competitive environment, the success of supply chains depends on its effective management, through the integration of material and flow between the different supply chain actors, minimizing costs, respecting the industrial constraints and achieving the customer service level required (Samaranayake, 2005). In this context, supply chain management is becoming increasingly important.

Supply chain network design (SCND) consists on determining the structure of a supply chain: facilities location and their capacities, as well as taking decisions concerning the operation and the functioning of the supply chain (Farahani *et al.*, 2013b). The structure and the functioning of a supply chain have an important impact on its future performance and costs. Hence, SCND is critical in order to achieve supply chain management objectives.

SCND models can be classified in function of supply chain management paradigms and in function of the decision levels evaluated: strategic, tactical and operational. In the next sections, we start by defining each supply chain management paradigm from a SCND perspective. After we present the different decision levels that are studied in SCND. Then, we review some SCND case studies conducted in different industries in order to provide a benchmark of different industrial applications of SCND. Finally, we characterize the SCND project of our case study.

1.1. Supply Chain Management Paradigms

In the current evolving industrial environment, supply chain networks must not only minimize costs, they also have to be agile and responsive and in the same time consider social and environmental factors. In that context, in the last years, new supply chain paradigms have emerged. These supply chain paradigms can be classified depending on the associated concerns and their focus area. There are many SCND studies associated with different supply chain management paradigms. Hereafter, we present a supply chain paradigms classification targeting SCND, based on a review conducted by Farahani *et al.* (2013b). The paradigms studied are lean supply chain management, agile supply chain management, green supply chain management, sustainable supply chain management and risk supply chain management.

1.1.1. Lean Supply Chain Management

Within the lean supply chain management paradigm, supply chains are mainly designed for the purpose of minimizing total costs. This paradigm was developed based on the lean management principles. Supply chains are developed in a way that non-adding value activities and resources are eliminated. Shen (2007) conducts a review on lean SCND models. He focuses on integrated supply chain design models. In other words, in models that integrate facility location decisions, inventory management decisions and distribution decisions in order to minimize total logistics costs. He presents three categories of models:

1. **Location-Routing Models**: These models integrate facility location decisions and vehicle routing decisions. Facility location, as the name suggests, refers to locating facilities (plants, warehouses, etc.) by minimizing total cost. Vehicle routing decisions

refers to defining minimal cost picking or delivery routes. Min *et al.* (1998) present a review of combined location-routing models.

2. **Inventory-Routing Models:** These models integrate vehicle routing and inventory management decisions. Kleywegt *et al.*(2002) provide a literature review on inventory-routing models. Inventory-routing models define optimal picking and delivery routes minimizing transportation and storage costs.

3. **Location-Inventory Models:** These models integrate facility location and inventory management decisions. Shen (2007) conduct a review on this type of models specially.

Even if location, inventory and routing decisions are dependent, in several cases they are treated separately. For example, Drezner (1995) provides a review on lean facility location models dealing only with location and allocation decisions. Zipkin (1997) writes a book addressing lean inventory management models.

Additionally, nowadays supply chains need to be designed in increasingly competitive markets. There are not a lot of lean SCND studies that consider the presence of competitors in the supply chain. However, this could influence the supply chain network structure. Farahani *et al.* (2013a) provide a literature review on competitive SCND. Other studies go further in the analysis of SCND by integrating horizontal collaboration between logistics networks in order to share flows and implement consolidation strategies (Pan, 2017). Literature dealing with lean SCND models is very large; we will go further on these models in the Section 1.2 of this chapter and in Chapters 3 and 4.

1.1.2. Agile Supply Chain Management

In a rapidly evolving industrial context, supply chains need to be continually adapted to answer to customers' needs changes. Hence, improving flexibility and responsiveness in supply chains is becoming a major issue. Agile supply chain management paradigm seeks to improve supply chains responsiveness and flexibility by reducing time-to market in a cost-effective way.

Agile supply chain management emerged with the integration of agile manufacturing and supply chain management. The objective of agile manufacturing is to provide organizations with different tools that allows responding to quick market changes controlling costs and quality requirements (Yusuf and Gunasekaran 2002). According to Gunasekaran *et al.* (2008), an agile supply chain can be defined as "a network of firms that is capable of creating wealth to its stakeholders in a competitive environment by reacting quickly and cost effectively to changing market requirements". They propose a framework for developing an agile supply chain based on three enablers that improve responsiveness and flexibility:

1. **Strategic planning:** Strategic planning defines the long-term interests of a company. In order to integrate agility in strategic planning, a company should develop global outsourcing strategies and establish strategic alliances in order to improve flexibility. In the same way, it must have close relationships with the end-users in order to evolve in function of market trends.

2. **Virtual enterprise:** "A virtual enterprise is based on developing partnerships based on core competencies for achieving agility in a supply chain environment. In a virtual enterprise, facilities do not longer operate as isolated entities; they operate as nodes in

a network of suppliers, customers and other specialized service functions. The objective is to allow a number of organizations to rapidly develop a common working environment" (Gunasekaran *et al.*, 2008). Consequently, the integration of the different business entities in the supply chain must be supported by appropriate IT management policies.

3. **Knowledge and IT management:** An effective IT management improves supply chain responsiveness. Information and knowledge should be shared and managed all along the supply chain in a way that it can face rapid changes in market conditions.

Agile SCND integrates the enablers defined before. For example, Dotoli *et al.* (2006) propose a SCND model for an integrated e-supply chain. An integrated e-supply chain is a network of physical business entities supported by an e-business network that allows improving responsiveness. In their model, they propose different performance measures such as transportation and process time, product quality, etc. that can be improved with e-links between the different supply chain entities. Argawal *et al.* (2007) define a set of variables related with supply chain agility: market sensitiveness, new product introduction, data accuracy, centralized and collaborative planning, process integration, use of IT tools, lead-time reduction, service level improvement, cost minimization, customer satisfaction, quality improvement, uncertainty minimization, trust development and resistance to change minimization. They use interpretive structural modeling in order to identify inter-relationships between these variables and after they classify them in function of their impact in the supply chain agility. Pishvaee and Rabbani (2011) propose a responsive SCND model that includes maximum delivery time constraints. They evaluate two scenarios. The first scenario allows direct shipments from plants to customers while the second scenario does not allow direct shipments, and it is necessary to use distribution centers. Liu and Papageorgiou (2013) provide a model in which they assume that the current capacity of the plants would not be enough to satisfy the rapidly increasing demand. Hence, they integrate capacity expansion variables in the model in order to improve responsiveness. Boubaker (2019) conducts a study in order to develop different models for assessing and improving supply chain agility. He develops a matrix defined based on situations that require agility in supply chain management. This matrix allows evaluating qualitatively the agility of a supply chain. He also propose two indicators to evaluate quantitatively the agility of a supply chain by modelling physical flow and information flow.

Finally, lean and agile strategies are frequently considered as opposites. However, some studies show that they can work together in order to find compromises between cost reduction and responsiveness improvement. To go further on this approach the reader can refer to Goldsby *et al.* (2006).

1.1.3. Green Supply Chain Management

With global warming, the depletion of natural resources and other environment problems, supply chains are more and more constrained to reduce their environmental impact. Green supply chain management is defined as "integrating the environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life" (Srivastava, 2007). Within the paradigm of green supply chain management, supply chains are designed with the aim of maximizing profits and at the same time minimizing environmental impacts.

In this way, green SCND can be defined as the integration of the environmental thinking when determining the structure of a supply chain: facilities location and their capacities, as well as taking decisions concerning the operation and the functioning of the supply chain. Waltho *et al.* (2019) provide a literature review on SCND models with a focus on carbon emissions policies. Carbon policies allow controlling the quantity of CO_{2eq} emitted by a supply chain by imposing a price, a limit or a tax. Waltho *et al.* (2019) define four types of carbon policies:

1. **Carbon tax:** In several countries, there are regulatory bodies, which are in charge of regulating the CO_{2eq} emissions. To this end, they apply a fixed charge/tax per unit of CO_{2eq} emitted. The hardest part in these cases is to define the correct rate in order to reduce CO_{2eq} emissions without having a major and negative impact in the profitability of the supply chains. Paksoy *et al.* (2011) present an example of a multi-objective SCND model including CO_{2eq} tax constraints in form of penalties per unit of CO_{2eq} emitted. Other examples that include carbon taxes can be found in Zeballos *et al.* (2014) or in Yang *et al.* (2013). Chelly *et al.* (2018) propose a supply chain technology selection stochastic model that integrates uncertainty in carbon tax. In some countries, when applying carbon tax policies, a progressive tax strategy is used. It means that carbon price evolves in function of changing social, economic and political circumstances.

2. **Carbon cap:** In this case, a limit (carbon cap) for carbon emissions is imposed to companies. As for the carbon tax policy, defining the carbon cap level is not a simple task. It is necessary to define a limit that does not affect the profitability of the company. In general, SCND models that integrate carbon cap policies define an upper bound for supply chain CO_{2eq} emissions. In some SCND models, carbon limits are imposed only for transportation operations, for example Soleimani *et al.* (2017) propose a model dealing with a recycling network in which they include carbon emission factors per unit of product and unit of distance for transportation operations. This model integrates a carbon cap policy defining a limit for CO_{2eq} emissions per unit of product. Other articles include other emissions sources, such as warehousing or production. For example, Peng *et al.* (2016) present a model that limits warehousing emissions by defining an amount of CO_{2eq} emissions per unit of inventory held.

3. **Cap-and-trade:** In this kind of policy, a regulatory body distributes credits to companies. Credits are distributed in function of carbon-caps defined also by the regulatory body. In that way, if a company produces less carbon emissions than its carbon-cap, it can sell the remaining credits to other companies in order to increase profits. Similarly, if a company needs to emit more than its carbon cap, it can buy credits from other companies. The price of credits are defined based on supply and demand. In the same way than for carbon cap policy models, cap-and-trade SCND models vary in function of the sources of CO_{2eq} emissions included in the model. For example, Rezaee *et al.* (2015) provide a model that integrates production and transportation emissions and defines different scenarios with different carbon market prices. Abdallah *et al.* (2010) provide a model that includes transportation, production, and warehousing emissions with a cap-and-trade policy. They define CO_{2eq} emissions for facilities in function of electricity consumption. To go further on this approach the reader can refer to Waltho *et al.* (2019).

4. **Carbon offset:** In this case, a carbon cap is also imposed to companies by a regulatory body. However, unlike the cap-and-trade policies, there is a penalty or offset cost if a

company exceeds its cap. Additionally, a company cannot sell credits if it produces less carbon emissions than its cap. An example of a SCND model integrating a carbon offset policy is presented by Altmann (2014). He does not present the carbon offset policy explicitly but he establishes a penalty if CO_{2eq} emissions exceed a determined level.

Chelly (2019) provides an overview of the environmental policies that have been implemented by governments. These policies include mainly carbon tax policies and cap-and-trade policies. As an example in the European Union, for cap and trade policies, carbon price per ton can vary between 0 and 30€. Concerning carbon tax policies, France has adopted a progressive carbon tax strategy in 2014. Initial carbon tax was fixed to 7€ per ton. Currently, French carbon tax is equal to 44.6€ per ton.

Carbon emissions are not the only way of integrating environmental impact in SCND models. SCND models can integrate other greenhouse gases (GHG) emissions or different types of waste. Mirzapour *et al.* (2013) study a SCND that includes a cap policy for waste. They estimate it based on a percentage of waste produced per product. We will go further in these models in the next section.

Green SCND models also deal with reverse logistics. Reverse logistics are defined as all the operations related with the recovery and the reuse of materials in a supply chain. Supply chain networks that integrate reverse logistics can be divided in two categories: networks including forward operations and recovery operations, namely **closed-loop networks**, and networks including only recovery operations namely **recovery networks**. Melo *et al.* (2009) provide a literature review on SCND models integrating reverse logistics operations.

Finally, Green SCND models can be extended also in order to integrate horizontal collaboration between supply chains to reduce carbon footprint. Pan *et al.* (2013) evaluate a logistics pooling strategy for two major retail chains in France. They define logistics pooling as "a solution for co-designing and sharing a common logistics network by partners (suppliers, clients, carriers, etc.) with a common objective". As a result they conclude that logistics pooling allows reducing CO_2 emissions significantly. To go further on horizontal collaborative logistics the reader can refers to Pan (2017).

1.1.4. Sustainable Supply Chain Management

Sustainable supply chain management extends the definition of green supply chain management in order to include economic, environmental and social dimensions. Under the sustainable paradigm, the main objective of supply chain management is to meet the supply chain objectives without compromising the survival and the well-being of the future generations.

Eskandarpour *et al.* (2015) provide a literature review on sustainable SCND. They make a classification of literature in function of the sustainable dimensions included: environmental, social and economic dimensions. Most of the articles integrate only the environmental and the economic dimensions, 74 over 87 articles reviewed, 10 integrate the three dimensions and 3 articles integrate only the social and the economic dimensions. In that way, they define two SCND categories:

1. **Environmental SCND:** Environmental models integrate economic and environmental dimensions. Eskandarpour *et al.* (2015) divide environmental SCND models into models applying a life-cycle impact assessment method and models using a partial assessment of environmental factors. Concerning the first ones, mainly three life-cycle

assessment methods are used: Eco-Indicator 99 (Ministry of Housing, Spatial Planning and the Environment, 2000), Impact 2002 and CML92. Each one of these methods develops different indicators based on a set of impact categories that are grouped in different damage categories (Ex. Human health, ecosystem quality, etc.). Even if there are several impact categories, SCND models integrate mainly four categories: climate change, biochemical oxygen demand, damage to human health and water footprint. Quariguasi-Frota-Neto *et al.* (2008) define a model in which they associate the different activities of the supply chain with different environmental impacts: global warming, ecotoxicity, photochemical oxidation, acidification, nitrification and solid waste. Chaabane *et al.* (2012) propose a model that integrates the life-cycle impact assessment approach by evaluating the GHG emissions as well as liquid and solid waste. Guillén-Gosálbez *et al.* (2009) provide a model for a hydrogen supply chain. They integrate damage to human health by using a metric called Disability Adjusted Life Years. This metric allows quantifying the number of life years lost for a person due to the damage caused. Concerning models using a partial assessment of environmental factors, they integrate constraints related to CO_{2eq} emissions for the different operations in the supply chain mainly. These models were reviewed in Section 1.1.3. Actually, **environmental SCND is the same as green SCND**. Even if in green SCND the sustainability term is not mentioned explicitly, integrating the environmental thinking in SCND contributes to the preservation of the future generations, hence **green SCND is part of sustainable SCND**.

2. **Social SCND:** In this case, social dimension as well as economic and/or environmental dimensions are integrated in SCND. The social dimension refers to addressing issues related with human rights and social justice. Chardine-Baumann and Botta-Genoulaz (2014) propose a framework to assess sustainable performance for a supply chain. Based on this assessment the social dimension can be addressed in SCND by integrating mainly three social fields: work conditions, societal commitment and customer issues. Concerning work conditions, a commonly used indicator to address this field in SCND is the number of jobs created. For example, Dehghanian and Mansour *et al.* (2009) propose a model for a sustainable recovery network. They maximize social benefits through job creation. To this end, they define a potential employment score per plant. Social commitment refers to decisions that allow improving population's health education and culture. Beheshtifar and Alimohammadi (2014) propose a model of location-allocation of clinics where they minimize the unequal access to health care centers. To this end, they minimize the variability of the access distance from each point of demand to the clinics based on the standard deviation. Bouzembrak *et al.* (2013) propose a model to design a network of treatment facilities for inland waterways sediments in the Nord-Pas de Calais region in France. They minimize the impact on the life quality for the habitants due to the sediments treatment. Finally, models dealing with customer issues seek to minimize negative impacts for each customer individually. Dehghanian and Mansour *et al.* (2009), in their model measure and minimize the risk that customers take when using hazardous materials in a recovery network.

1.1.5. Risk Management in Supply Chain Management

In an evolving industrial context, supply chains must face unexpected events that could affect negatively the performance of a supply chain. The objective of risk management is to decrease or eliminate the effect of these unexpected events by implementing risk identification, quantification, mitigation and elimination strategies.

According to Chopra and Sodhi (2004), there are nine supply chain risk categories: disruptions, delays, information systems, forecast, intellectual property, procurement, receivables, inventory and capacity. The disruptions category refer to any unexpected event that could affect material flow anywhere in the supply chain *i.e.* natural disasters. Delays category, as the name suggests, refer to any problem that could delay any process in the supply chain. Information systems category groups all the risk related with information systems failures. Forecast category refers to any error related with demand projections. Intellectual property category integrates risks related with the outsourcing of manufacturing processes. Procurement category groups risks associated with unexpected increases in acquisition costs. Receivables category refers to risks associated with the inability of a company to retrieve receivables. Finally, inventory and capacity categories group all the risks related with mistakes on inventory and capacity previsions.

SCND integrates risk management by taking into account the uncertainty associated with the different supply chain parameters. Govindan *et al.* (2017) conduct a review on SCND under uncertainty. They propose a classification of SCND models according to the uncertain included parameters. Based on their review, the most frequently studied uncertain parameters in forward SCND are demand, costs of activities, capacity of network facilities/transportation links, supply quantity for network facilities and availability of network facilities. Rodriguez *et al.* (2014) propose a SCND model for a spare parts supply chain that considers demand uncertainty. They consider that demand is a random continuous parameter that follows a Poisson distribution. Based on this distribution, they define a targeted demand that is equal to the mean demand plus an extra demand level defined in function of the standard deviation of the distribution. The safety stock is defined based on the desired customer service level. Warehouses and factories capacity expansion is also considered. Fallah *et al.* (2015) use fuzzy set theory in order to integrate uncertainty to demand and cost in a competitive closed-loop SCND model. To this end, they define a linear function for demand based on market base and price elasticity. Market base and price elasticity are considered fuzzy variables. Marufuzzaman *et al.* (2014) propose a SCND model for a biofuel distribution network that integrates risks associated with facilities availability. In their model, there are mainly three types of facilities: harvesting sites, intermodal hubs and biorefineries. Harvesting sites deliver intermodal hubs, and after intermodal hubs deliver biorefineries. They define a disruption probability function per intermodal hub. In case of disruption, harvesting sites can deliver directly the biorefineries as an emergency alternative, which cost much more than normal deliveries.

Uncertainty can be integrated to other supply chain parameters such as supply time, safety-stock levels, social parameters, etc. To go further on SCND models under uncertainty the reader can refer to Govindan *et al.* (2017).

1.2. Strategic, Tactical and Operational Decisions

SCND models can also be characterized in function of the decision levels with which they deal. According to Farahani *et al.* (2013a) SCND decisions can be grouped in three different levels: strategic, tactical and operational.

1.2.1. Strategic Level

The strategic level addresses the structure of the logistics network by defining the number, the location and the allocation of the facilities, their capacity and production technologies used. It must consider transportation channels between facilities, closeness to markets and to suppliers, joint ventures and strategic alliances (Schmidt and Wilhelm, 2000). The strategic level concerns long-term decisions (2 to 5 years' timeline) which are difficult to change (Misni and Lee, 2017). SCND literature dealing with strategic decisions is very large. Melo *et al.* (2009) conduct a literature review on facility location models. They classify models dealing with location and allocation decisions according to the structure and the basic features of the supply chain network addressed: the number of layers and location layers, the number of commodities, the time horizon and demand behavior. The number of layers refers to the number of stages of the supply chain (suppliers, distribution centers, etc.). Location could be fixed in some of the layers. The number of commodities refers to products characteristics: single-product and multiproduct. Time horizon refer to the number of periods for which the supply chain design will be planned: single-period and multi-period models. Finally, demand could be known over the time horizon, and hence, deterministic or unknown and variable and hence, stochastic. Melachrinoudis and Min (2007) propose a warehouse network design model with two layers: suppliers and warehouses. This model allows determining the optimal location of the warehouses: single location layer. Flow is aggregated in one product (single product), and only one period is evaluated in the time horizon. Salema *et al.* (2007) propose a three layers SCND model for a recovery network composed by warehouses, disassembly centers and factories. In this case, location is decided over the three layers. They propose a multi-product model and a single product (aggregated) model. Demand is considered stochastic by evaluating a set of potential scenarios. Time horizon is limited to one period. Hugo and Pistikopoulos (2005) develop a model for chemical supply chain networks. There is a single location layer of sites providing chemical products to different markets. In this case, time horizon is extended to several periods. Demand is known and multiple products are considered. To go further on facility location models dealing with strategic decisions the reader can refer to Melo *et al.* (2009).

Misni and Lee (2017) conduct a literature review on strategic, tactical and operational decisions in reverse logistics. Concerning strategic decisions, it is very important to take into account environmental legislations in supply chain design. Environmental legislation could affect the structure of the network. Additionally, product design takes greater significance in reverse logistics; product design affects the way in which materials are recovered and hence, the recovery network.

1.2.2. Tactical Level

The tactical level deals with decisions related with material flow management policies: production levels, transportation modes, flow passing through facilities, inventory levels and lot sizes. Material flow decisions must be supported by IT and knowledge management decisions. The tactical level concerns medium term decisions (1 to 2 years' timeline). They should take into account strategic decisions constraints.

There is a variety of SCND models that integrate strategic and tactical decisions. Melo *et al.* (2009), in their literature review, identify a set of tactical decisions other than allocation-location decisions that are integrated in facility location problems: inventory, procurement, production and transportation modes. Erlebacher and Meller (2000) develop a SCND model that determines optimal inventory policies at distribution centers. To this end, they integrate unit-holding costs, ordering costs and transportation costs in their model. They assume that these costs are constant for all the distribution centers. Eskigun *et al.* (2005) propose a model for a vehicle distribution network that integrates transportation mode selection decisions. In the supply chain presented, plants that produce vehicles have two choices: The first choice is to pass through a vehicle distribution center and after deliver the customer. In this case, rail freight is used to deliver the vehicle distribution center and road freight is used between the vehicle distribution center and the customer. The second choice is to deliver customers directly using road freight. Jang *et al.* (2002) integrate inventory, procurement and production decisions by dividing the SCND problem in four modules: supply chain network design optimization module, planning module for production and distribution operation from raw material suppliers to customers, model management module and data management module. Within the first module, the network design problem is defined. It is divided in three sub-problems. The first one deals with the location of suppliers for the manufacturing plants, the second one with the location of plants and warehouses and the third one with the location of distribution centers that serve the final customers. Within the second module, a model is proposed for defining production and distribution capacities for each one of the sub problems defined in the first module. Location-inventory models presented in Section 1.1.1 address strategic location decisions and tactical inventory decisions too.

We can find also models dealing with only one tactical decision in literature. For example the classical Economic Lot Size model which allows estimating optimal order quantities in function of ordering and inventory costs (Simchi-levi *et al.*, 2014). Meixell and Norbis (2008) conduct a literature review on transportation mode and carrier selection models. We will go, further on these models in Chapters 3 and 4.

In reverse logistics, from a tactical point of view, some particular issues need to be considered. When manufacturing products, a company needs to determine which products will be recovered and determine flow policies for recovered products. Integrating recovered products flow affects the capacities of the transportation channels as well as the facilities in the network. For that reason, it is necessary to determine the volume of products that will be recovered per period during the time horizon. Additionally, inventory policies for recovered products should be defined. Finally, depending on the quality of the recovered product, the remanufacturing processes and costs may vary, thus, it is necessary to design remanufacturing processes in function of the quality of the product recovered (Misni and Lee, 2017).

1.2.3. Operational Level

The operational level concern day-to-day decisions. It deals with operations scheduling in order to deliver products in time and achieve the desired customer-service level. Operational decisions include production scheduling, distribution scheduling and route scheduling. Operational decisions must respect constraints resulting from decisions in the strategic and the tactical level.

Early research in assembly scheduling and network scheduling is conducted by Schmidt and Wilhelm (2000). Russell and Taylor (1985) study different scheduling policies on an assembly shop by simulating different scenarios. The scenarios vary in function of the job structure, due date assignment rules, labor assignment rules and item sequencing rules. Performance indicators evaluated in each one the scenarios are job flow time, mean assembly delay and tardiness. Phillips *et al.* (1997) provide a network-scheduling model. In their model, each node in the network is a machine, and arcs connecting the machines define the distance between them. Each product must follow a defined path. The objective is to minimize the average completion time for the network. Chandra and Fisher (1994) develop a model that integrates production and route scheduling. They proposed two approaches: the first approach determines production and route scheduling separately and the second approach integrates them. It is demonstrated that the integration between the production and the distribution functions could lead to cost reduction in a company.

A classic model dealing with route scheduling decisions is the Vehicle Routing Problem (VRP). The objective of the classical VRP is to define an optimal set of delivery routes for a set of vehicles with the same characteristics. There is one central depot and a set of delivery points. Each vehicle starts and ends its route at the central depot. Each delivery point is visited at most once. There exists several extensions of the VRP that include other industrial constraints: time windows at the facilities, driving time constraints, capacity constraints, etc. Braekers *et al.* (2016) conduct a literature review on the VRP and its main extensions. Vehicle routing problem can be extended in order to include inventory management and production scheduling. For example, the Inventory Routing Problem (IRP) defines optimal delivery routes by minimizing transportation and inventory costs (Bertazzi and Speranza, 2012).

There exists also models that integrate operational routing decisions with strategic location decisions in the early supply chain design phase. Chan *et al.* (2001) propose a stochastic SCND model that addresses location and routing decisions. They divided the model in two parts: the first one defines the loads at each one of the facilities and the second part defines optimal routes from each regional depot to the respective demand nodes. A similar approach is proposed by Tuzun and Burke (1999). They propose an iterative tabu search algorithm that uses the outputs of the location model at the vehicle routing problem, and the outputs of the vehicle routing problem to improve the results of the location problem. This process is repeated iteratively.

Finally, in reverse logistics, operational decisions include scheduling disassembly and remanufacturing operations and the integration of the recovery process in routes scheduling (Misni and Lee, 2017).

1.3. SCND Case Studies

In this thesis, we will develop SCND models for the Aeronautic industry. Hence, in this section, we conduct a literature review of different SCND industrial case studies. We include some of the cases studies reviewed by Melo *et al.* (2009). The main objective is to provide a benchmark of different industrial applications of SCND and its potential benefits.

As it will be explained in detail at the end of this chapter, in Section 1.4, the Airbus Helicopters (AH) case study will be conducted under the lean supply chain paradigm and the sustainable supply chain paradigm and it will address the strategic and the tactical SCND decision levels. Hence, we focus on case studies including these aspects. Table 1 provides a summary of the case studies reviewed in this section.

Case Study	Industry	Supply Chain Paradigm		cision levels includ	
		Lean	Sustainable	Strategic	Tactical
1.3.1. Camm et al. 1993	Consumer Goods	X		X	X
1.3.2. Karabakal et al. 2000	Automotive	X		X	X
1.3.3. Kumar and Wassenhove 2002	Automotive	X		X	
1.3.4. Laval et al. 2005	Computer Hardware	X		X	
1.3.5. Fleischmann et al. 2006	Automotive	X		X	X
1.3.6. Chandiran and Surya Prakasa Rao 2008	Automotive		X	X	X
1.3.7. Ramudhin and Benkaddour 2010	Aeronautic	X		X	X
1.3.8. Tang et al. 2013	Aeronautic	X		X	
1.3.9. Colicchia et al. 2015	Food		X	X	
1.3.10. Varsei and Polyakovski 2016	Food		X	X	X
1.3.11. Feitó-Cespón et al. 2017	Recycling		X	X	X
1.3.12. Laurin and Fantazy 2017	Retail		X	X	

Table 1.1. SCND case studies reviewed

1.3.1. Procter & Gamble Case Study (Camm *et al.*, 1993)

Procter & Gamble (P&G) is a multinational company that produce fast moving consumer goods (laundry detergents, shampoos, diapers, etc.). In 1993, P&G launched a project called Strengthening Global Effectiveness (SGE). The objective of this project was to “streamline work processes, drive out non value-added costs and eliminate duplication”. One of the levers of action of this project was the redesign of the P&G supply chain in North America. There were five launchers for the project: 1) the deregulation of transportation which reduced transportation costs, 2) compact packaging was implemented for several products of P&G which allowed increasing the capacity usage of transportation modes, 3) quality improvement allowed considering the possibility of reducing the number of plants, 4) product life cycles reduction and 5) capacity excess. In that context, P&G needed to consolidate plants and to optimize the supply chain network in order to reduce global logistics costs and improve speed to market. Before the study, North America supply chain was composed of 60 plants, 15 distribution centers and hundreds of customers.

P&G created 30 cross-functional product strategy teams based on product categories and a distribution and customer service team. The product strategy teams were in charge of plants consolidation and product-sourcing optimization, and the customer service team was in charge of optimizing the distribution network to the customers. Plants consolidation scenarios that could be evaluated were countless. For that reason product strategy teams were supported by the quantitative analysis and operations management faculty of the University of Cincinnati in order to select the best scenarios to consider in the analysis.

Two SCND models were developed in order to support the analysis: a distribution center location model and a product-sourcing model. Results obtained with the distribution center location model were used as input in the product-sourcing model, and results in the product-sourcing model were used to improve the distribution network. The distribution center model was developed based on the classical Uncapacited Facility Location model (Verter, 2011). The objective of this model was to allocate distribution centers to different customer zones. It integrated mainly handling costs, inventory costs, transportation costs and duties associated with borders crossing. The product-sourcing model was defined as a transportation model per product category. In this model, customer zones and distribution centers are assigned to plants based on manufacturing and warehousing costs at the plant and transportation costs.

As a result, P&G achieved 200 millions of savings per year and reduced the number of plants by 20%. SCND models in this project were mainly developed under the lean supply chain paradigm and the decisions evaluated include strategic and tactical decisions.

1.3.2. Volkswagen of America Case Study (Karabakal *et al.*, 2000)

Volkswagen of America imports, markets and distributes Volkswagen and Audi vehicles in the United States. Vehicles are assembled in Germany and Mexico. In 1995, Volkswagen launched a project in order to optimize its vehicle distribution process. The objective of the project was to reduce costs and improve responsiveness.

The vehicle distribution network was composed by Original Equipment Manufacturers (OEMs), franchised dealers and end users. OEMs sold cars to dealers and dealers sold cars to the end users. In the past, Volkswagen objective was to maximize the cash flow of the company. Hence, vehicle dealers were considered as end users by the OEMs; OEMs, and dealers worked independently. Regarding the distribution system, vehicles arrived initially to seaports that worked as distribution centers. After they were sent to dealers.

In a competitive environment where vehicles variety increased exponentially, priorities started to change. The need arose for reducing global distribution costs and improving the customer service level. With the old distribution network, it was not possible to reduce global cost given that each supply chain layer worked separately, and it was very difficult for dealers to ensure first choice availability for customers. In this context, a study was conducted by Karabakal *et al.* (2000). They did a simulation in order to evaluate the location of new distribution centers near to metropolitan markets that improve responsiveness and reduce storage cost at dealers. After evaluating several scenarios, they found that by modifying the current distribution network with the inclusion of new distribution centers, transportation cost could be reduced and customer-service level could be improved simultaneously.

After the study, Volkswagen opened a set of pilot cases. Midwestern dealers reduced their costs and improved their service levels significantly. For southeast dealers, benefits were smaller because of their proximity to seaports. Additionally, several big dealers were reluctant to reduce their stock. For them it meant losing a competitive advantage against small dealers, which had less ground stock availability. In 1997, a new range of vehicles arrived to the US market. Initial demand for these vehicles was very high which resulted in low inventory availability. Pilot distribution centers were not able to maintain a stock level that allows maintaining profitability for these vehicles. Hence, the pilot cases were ended.

Even if the results of the study were not implemented because of a change in the supply and the demand, Volkswagen changed its priorities in order to optimize costs and customer service. Thus, they started seeing the vehicle distribution system as a whole, including dealers and end users. SCND models in this case study were developed under the lean supply chain management paradigm and decisions evaluated include strategic decisions concerning the location of distribution centers and tactical decisions concerning transportation and inventory management policies.

1.3.3. Jaguar Case Study (Kumar and Van Wassenhove, 2002)

Jaguar is the luxury brand of Jaguar Land Rover, a British car manufacturer. In 1998, Jaguar decided to produce the new Jaguars X-400 in the Ford's Halewood plant in the UK. This decision was taken based on its capacity to produce big volumes, its location and costs. However, compared to the rest of the Ford plants, Halewood plant was not the most appropriate in terms of quality and competitiveness. For that reason, Jaguar decided to launch a SCND project conducted by David Hudson in order to transform the Halewood plant to match the quality and competitiveness level of the other plants.

This project was an opportunity for Jaguar to optimize the whole supply chain: suppliers, service providers, inventory, etc. David Hudson structured the project under the lean supply chain management paradigm along four different axes:

1. **Early supplier integration and modularity**: Supplier was integrated in early product design phases. To this end, modularity concept was implemented for the X-400 interior systems. As a result, there were only four suppliers for the interior systems; this facilitated supplier integration in product design.

2. **Suppliers' rationalization and location**: For the S-type models, Jaguar used to work with 350 suppliers. For the X-400, suppliers panel was reduced to 130 suppliers. Suppliers delivering big modules or subassembly were located close to the Halewood plant. The majority of the parts were sourced from suppliers located within a 161 km radius. Based on suppliers location different deliveries policies were defined. For suppliers in UK, it was implemented a pull-strategy based on requirements. Suppliers located in Europe delivered Halewood in a daily basis and for suppliers located in the rest of the world deliveries were planned, based on a lead-time of 21 days.

3. **Logistics Outsourcing**: It was decided to implement a strategy called Nirvana. The objective of this strategy was to have only one person at Jaguar managing the entire supply chain. Hence, activities different to the core business activities needed to be outsourced. Logistics providers were in charge of inbound logistics and internal logistics. Jaguar personnel were involved only in the assembly process. Concerning inbound logistics, logistics providers developed an "intelligent collection system". Based on forecast, logistics service providers defined a picking schedule specifying products quantity requirements and shared it with suppliers and drivers. Drivers were responsible of ensuring that the collected quantities correspond to specified quantities in the picking schedule. If it was not the case, they must refuse the shipment.

4. **Process Design:** Before the project, the main objective of the Halewood plant was to minimize costs and quality and productivity were secondary objectives. With this new project, priorities changed, quality and productivity became primary objectives. Additionally a "Center of Excellence" was created in order to promote lean manufacturing practices.

After launching the project, some problems were encountered by Jaguar. For example, suppliers providing modules did not anticipate the challenges of the new system. For that reason, some adjustments were made in order to put the project on the right track. This project allowed achieving significant quality and productivity improvements.

1.3.4. Hewllett-Packard Imaging and Printing Group Case Study (Laval *et al.,* 2005)

Laval *et al.* (2005) present a study conducted for the Imaging and Printing Group (IPG) of Hewllett-Packard by the Strategic, Planning and Modelling Team (SPaM). The objective of this study was to provide a model to support the supply chain redesign process in order to reduce contract partners in the Europe, Middle East, and Africa (EMEA) region in charge of postponement and distribution activities. In other words, it was necessary to provide a model that allows defining the optimal location of postponement facilities.

In this way, the IPG supply chain studied was composed mainly of postponement facilities and demand points. The SPaM team aggregated demand points in 20 demand areas. For each area, three delivery alternatives were defined: delivering products through warehouses, delivering products through an intermediary stocking point or delivering products directly to end users. Additionally, 10 possible postponement locations were evaluated and 20 product categories.

To address the IPG supply chain design problem, the SPaM team proposed a green-field combined approach consisting on a mixed integer linear programming (MILP) model and a scenario-based model. With the MILP model an optimal solution was provided. In the scenario-based model, a group of experts defined manually a group of improved scenarios based on experience. The costs of modifying the supply chain network were not included in these models. The MILP model was run using a sophisticated solver and the scenarios for the scenario-based model were defined using an Excel worksheet. Results obtained with the scenario-based model were used after to identify inconsistencies and improve the solution of the MILP model with the help of the SPaM team in order to define a true optimal solution. Additionally, results obtained with the scenario-based model as well as the SPaM analysis could be also used to improve the MILP model by adding more real world constraints.

Finally, based on the solution obtained, experts defined a set of recommendations for the company. Estimated potential savings amount to $10 millions of supply chain costs maintaining the current service level.

1.3.5. BMW Case Study (Fleischmann *et al.*, 2006)

In 2000, BMW launched a project in order to optimize its product allocation process to sites. Before launching this project, product allocation was made manually using Excel sheets. Allocation was made based mainly on the technical attributes of each site: personal skills and site specialization. In some cases, the production of one product could be split and allocated to more than one site. Planners decided on production split based on plants usage. In the same way, some products could be potentially allocated to several sites. In these cases, planners decided on product allocation based on their judgement or trying each one of the possible scenarios. By doing this way, product allocation was a time consuming activity and it was difficult to evaluate multiple strategies simultaneously. Additionally, capacity was calculated for each site as a whole, even if some processes inside each site should be treated separately (*i.e.* paint shop and specific assembly bodies). Supply and distribution processes were not taken into account in the products allocation process.

Fleischmann *et al.* (2006) developed a MILP multi-commodity network flow model in order to support and improve the product allocation model. This model included mainly two types of decision variables: product allocation to plants variables and flow variables for production, distribution and supply. This model was afterwards extended in order to evaluate investment decisions and to consider capacities and flexibility in detail. The objective function was the discounted cash flows for operational costs and investments.

The model was deployed on a real BMW instance using ILOG OPL Studio, an environment for developing MILP models using the solver CPLEX. Results presented in the study of Fleischmann *et al.* (2006) are limited to a subset of 36 products and 6 production sites because of BMW privacy policies. Two strategies were evaluated. In the second strategy, production split freedom degree is increased from two to three sites for one of the products, which is critical. As a result, cost is reduced by 9.3 billions € with strategy 1 compared to the current scenario. Strategy 2 allows achieving a 0.1 billions € supplementary cost reduction.

Results obtained demonstrate that by supporting product allocation process with the proposed MILP network flow model an important cost reduction could be potentially achieved. Additionally, it allows evaluating different product allocation scenarios quickly and the planning effort is reduced. BMW network flow model was developed under the lean supply chain paradigm. In addition, the decision levels evaluated include strategic allocation decisions and tactical decisions concerning flow policies.

1.3.6. Automobile Battery Manufacturer Case Study (Chandiran and Surya Prakasa Rao, 2008)

India legislation obliges battery manufacturers to be responsible of used batteries collection and delivery to recycling facilities. In that context, integrating reverse logistics in supply chain network design process becomes an important issue. Integrating reverse logistics require defining the recycling facilities locations as well as the different recovery transportation channels. Chandiran and Surya Prakasa Rao (2008) conduct a case study for a leading manufacturer of lead-acid automotive batteries. In this case, supply chain is composed mainly by suppliers, plants, warehouses, franchisees and recycling facilities. Virgin lead-acid is provided by suppliers located in New Zealand and Australia. Regarding the forward distribution process, batteries are sent from plants to a set of regional warehouses. Warehouses sell batteries to franchisees, which then sell batteries to final customers or retailers. The recovery of used batteries take place when customers buy new batteries from retailers. There is an incentive for customers who return used batteries to the retailers. After, retailers send batteries to franchisees. At this point two possibilities were evaluated in the case study: case 1) franchisees cumulate a big quantity of batteries and after send them to warehouses, which then sell the used batteries to recycling facilities. Case 2) franchisees send batteries directly to the recycling facilities.

The model proposed by Chandiran and Surya Prakasa Rao (2008) is a MILP. The location of plants and customers are fixed. Warehouses, franchisees and recycling facilities locations are decision variables. Costs included are transportation and holding costs of new and used batteries, and fixed costs for warehouses and franchisees. There are also variables defining the number of (used or new) batteries transported between the different facilities.

The model was run using an optimizer tool called LINDO. Results obtained show that in case 2 cost is reduced by 8.25% compared to case 1. However, if used batteries are shipped directly from franchisees to recycling facilities, manufacturers could lose control over the recovery process. Hence, it is recommendable to define incentive policies to ensure that the franchisees perform the recovery process. The results obtained and the model proposed were used by the Indian batteries manufacturer to support a make or buy decision concerning the whole reverse logistics process. In this case, the SCND model was developed under the sustainable supply chain paradigm. Decisions include strategic decisions such as the location of warehouses, franchisees and recycling facilities and tactical decisions concerning flow policies.

1.3.7. Jet Engine Manufacturer Supply Chain Case Study (Ramudhin and Benkaddour, 2010)

Ramudhin and Benkaddour (2010) conduct a SCND case study in the aeronautic industry for a jet manufacturer. The supply chain studied integrates modular conception. This means that products are divided in modules that are assembled separately in parallel, to then assembly the final product. In that way, the supply chain addressed is composed by raw materials suppliers, subcontractors (which assembly modules) and customers (jet manufacturers). The objective of the study is to develop a model that allows defining sourcing policies for each part and assigning parts to modules optimally.

The authors propose a multi-echelon, multi-period, deterministic MILP SCND model that allows assigning parts to the different modules, defining suppliers for each part and defining subcontractors for each module, minimizing total costs: raw materials assignment costs to suppliers, modules assignment costs to subcontractors, products assignment costs to modules, supply costs, inventory costs and transportation costs.

They run the model using CPLEX for an illustrative example with two finished products. They evaluate different scenarios in which the lower bound for the subcontractors' capacity utilization varies. Results obtained show that the model is coherent and allows to perform different what-if analysis. However, no industrial recommendations or inbound SCND guidelines for the aeronautic industry could be inferred by this study.

1.3.8. Aircraft Wing Box Case Study (Tang *et al.*, 2013)

In an evolving context, with the emerging of joint ventures and the early integration of the suppliers in the aeronautic industry, supply chain design is becoming increasingly critical in this industry. Tang *et al.* (2013) propose a MILP SCND model for an aircraft wing box. Traditionally aeronautic supply chains are composed by raw material suppliers, intermediate processing facilities, a final assembly facility and customers. In the wing box supply chain studied, intermediate processing facilities are in charge of sub assembling the different parts of the wing box based on its work breakdown structure (WBS). It includes ribs, skins, stringers and spars. Additionally, intermediate processing facilities could be domestic or overseas facilities.

Tang *et al.* (2013) do not present the MILP developed in detail. However, main decision variables concern the location of the intermediate processing facilities as well as flow between the different facilities. The objective is to minimize the overall logistics costs of the supply chain. Due to the aircraft industry privacy policies, the input data in this study are obtained by extrapolating data available in literature for the F-86F model.

The main objective of this study is to provide a SCND model that could be applied to the Aeronautic industry and to demonstrate its capabilities through different tests conducted using the input data defined before. Mainly three tests are conducted; they are evaluated based on the net present value (NPV) of the cost:

1. **Labour rate modification:** The model is run for different scenarios varying the overseas facilities labour rate in function of the domestic labour rates (overseas labour rate = X % of domestic rates). As expected, when overseas labour rates are reduced and are smaller than the domestic rates, more overseas facilities are opened and the NPV decreases. On the contrary, when overseas rates increase and are bigger than the domestic rates, no overseas facilities are opened and the NPV gets stable at some point.

2. **Change in demand:** Uniform, trapezoidal and triangular demand profiles are tested. As expected, the highest NPV is obtained for the triangular distribution. This is due to demand peaks; new facilities need to be created in order to face demand increase. The smallest NPV is obtained for the uniform distribution.

3. **Make vs buy decisions:** Make or buy decisions are evaluated for subassemblies made by the intermediate processing facilities. To this end, a set of external suppliers are added to the supply chain. Thus, the company has to choose between making the subassemblies and outsourcing their production to external suppliers. Several scenarios are evaluated by varying the purchasing price proposed by the external suppliers. As expected, for small values of the purchasing price (20% or 40% of the baseline manufacturing cost) all the subassemblies are outsourced, and as the purchasing price increased more parts are produced in in-house facilities.

Finally, no industrial recommendations or supply chain design guidelines for the aeronautic industry could be inferred by this study because of industrial data unavailability. However, the MILP model proposed is proven to be consistent and can be applied when locating intermediate processing facilities in the aeronautic industry.

1.3.9. Lindt & Sprüngli Case Study (Colicchia *et al.*, 2016)

Lindt and Sprüngli is a Swiss chocolate manufacturer. Colicchia *et al.* (2016) propose a model in order to address a SCND problem for the distribution of perishable food products. They apply this model to a real case for Lindt and Sprüngli. The classical distribution network for perishable food goods is composed by a central warehouse, a set of transit points and a set of demand points. Warehouse delivers the transit points, which have moderate inventory levels. After products are sent from the transit points to the demand points. In the model proposed, products are delivered using a Full Truck Load (FTL) delivery method between the central warehouse and the transit points and using a Less than Truck Load (LTL) delivery method between the transit points and the demand points.

The model proposed is multi-objective mathematical programming model. Two objectives are minimized: costs and CO_2 emissions. Main costs include transportation and storage costs. In the other hand, in order to estimate transportation CO_2 emissions, different LTL and FTL emission factors are defined in function of the use rates of vehicles. CO_2 emissions for the storage activity are estimated based on the number of kWh consumed per facility. The multi-objective modelling approach defined converts CO_2 emissions in to a monetary objective by defining a fixed cost per kilogramme of CO_2. After a coefficient is assigned to the cost and the environmental objective according to the company policy.

The Lindt and Sprüngli case study is conducted for a distribution network located in Italy. Currently, there is 1 central warehouse, and 22 transit points. Demand is aggregated in 81 demand points. Location is fixed for the central warehouse and the demand points, only the location of the transit points needs to be defined. In addition to the existing 22 transit points, 16 other potential locations for the transit points are added in function of the distribution of the demand points. Warehouse CO_2 emissions are estimated based on energy-consumption historic data. It is assumed initially that cost per kg of CO_2 is equal to 199 € based on company suggestions.

The model is run for three optimization scenarios. In the first scenario, only the cost objective function is taken into account. As a result, cost is reduced by 3.1% and CO_2 emissions are reduced by 0.73% compared to the current scenario; 17 transit points are opened compared to 18 existing transit points in the current scenario. In the second scenario, only the environmental objective is included. In this case, CO_2 emissions ae reduced by 15.1% but cost increase by 3.5%; only 8 transit points are opened. In the third scenario, both objectives are included in the objective function with equal weights. In this case cost and CO_2 emissions are reduced by 3% and 2.8% respectively; 16 transit points are opened in this case. In the three scenarios, CO_2 emissions are reduced, even in the first scenario where only cost is included in the objective function. The main driver of CO_2 emissions reduction is related with energy consumption savings concerning the refrigerating activities.

Finally, the SCND model presented in this case study is designed under the sustainable supply chain paradigm and includes location and allocation decisions at the strategic level.

1.3.10. Wine Company Case Study (Varsei and Polyakovskiy, 2016)

As it was seen in Eskandarpour *et al.* (2015), there are not a lot of studies including social, environmental and economical dimensions at the same time. Motivated by this gap, Varsei and Polyakovskiy (2016) propose a SCND model that includes these three dimensions for the wine industry. They propose a multi-objective MILP and then they apply it to evaluate the design of the supply chain for an Australian wine company.

Traditionally Wine supply chain is composed by suppliers, wineries, bottling plants distribution centers and demand points. Suppliers provide grapes, bottles, etc. to wineries and bottling plants. The wineries produce the bulk wines and then send them to bottling plants. Using the bulk wines, the bottling plants produce bottled wines that are afterwards sent to distribution centers, which deliver bottled wines to the different demand points. In the Australian company considered by Varsei and Polyakovsky (2016), one winery produces bulk wines. Bottles are produced at the same site. Then they are delivered directly to demand points using road and rail freight, with a preference for road freight in almost all the cases.

In the model developed, there are three objectives: 1) minimize purchasing, storage, production, transportation and facilities fixed opening costs, 2) minimize transportation CO_2 emissions and 3) maximizing the social impact of facilities. Sea, rail and road transportation modes are included. Emissions for transportation modes are calculated based on emission factors published by the International Federation of Wines and Spirits. Concerning the social impact, different social impact coefficients are defined per potential facility according to the region in which it is located. These coefficients are defined in function of unemployment rate and regional gross domestic product (GDP). The smaller is the GDP and the higher is the unemployment rate of a region the bigger is its social impact coefficient. In the case study, it is assumed that the location of the demand points are fixed. Location is decided only for bottling facilities. The other variables define flow between the different facilities.

Using IBM ILOG CPLEX the model is run using the ε-constraint method. 9 supply chain configurations are obtained in function of objectives prioritisation. Three of them allow improving the three objectives compared to the current scenario. The first one reduces cost by 15.9% and CO_2 emissions by 55.1% and improves the social impact by 14.3% compared to the current scenario. The second one reduces cost and CO_2 emissions by 13.3% and 63.9% respectively, and improves social impact by 26.7%. Finally the third one reduces cost and CO_2 emissions by 14.7% and 58.4% respectively and improves social impact by 28.3%. Important CO_2 emissions reductions are due to bottling plant relocation and sea transportation mode inclusion. In the current supply chain, bottling plant is located far away from main demand points and CO_2 emissions in the wine industry are mostly due to bottled wines transportation because of bulky and heavy packages.

Results obtained show the gap between the current supply chain network and the sustainable supply chains networks obtained. Even if there is a capital investment required to modify the existing network and open a new bottling facility, it is amortized by transportation costs reduction. Additionally, integrating sustainability is an increasingly important issue in this industry; therefore, supply chain re-design process in order to improve social impact and reduce environmental impact is essential for companies.

1.3.11. Cuban Recycling Supply Chain Case Study (Feitó-Cespón *et al.,* 2017)

Recycling supply chain is managed by state-owned Enterprises for Raw Material Recovery (ERMR) in Cuba. During the last years, there has been an increase in waste generation in the plastic recycling supply chain. Hence, the redesign of the supply chain needed to be studied. Feitó-Cespón *et al.* (2017) propose a SCND model for a recycling network. In this case, supply chain is composed mainly by waste providers, gathering centers, recycling plants and customers. Waste providers deliver waste to gathering centers, which clean and classify it. After, the gathering centers send material to recycling plants. Recycling plants treat material and after sell the recycled products to end customers. They apply the model developed to the Cuban recycling network case.

Feitó-Cespón *et al.* (2017) propose a stochastic multi-objective mixed integer nonlinear SCND model with 3 objectives: minimization of the operating cost, minimization of the environmental impact and maximization of the customer service. Costs include fixed costs and operating costs of the recycling plants and the gathering centers as well as transportation costs. The environmental impact is measured using the life cycle assessment Eco-indicator 99 method. This method defines a set of alternatives for the different processes per life cycle phase concerning energy generation, transportation mode used, etc., and for each alternative it defines a score (eco-indicator points) per unit of measure. Scores must be calculated for each operation in the life cycle and afterwards added to calculate the global environmental impact. The higher is the number of points, the greater is the environmental impact. In the model proposed, the environmental impact is measured based on energy consumption, water consumption, pollution generated by facilities and transportation and the effect of disposing one unit of product in landfill after consumption. For each one of these elements, a fixed number of eco-indicator points per unit of measure is defined. The customer service is measured as the demand served. Decision variables included concern material flow, the quantity and the location of facilities, and the quantity and type of transportation modes.

The Cuban recycling plant studied is currently composed by 18 waste providers, 1 recycling plant and 18 customers. There are no gathering centers; waste is sent directly from the waste providers to the recycling plant. In the case study, two new potential locations for the recycling plant are included. Waste providers and customer locations are fixed. Model is run for 9 scenarios that vary in function of waste generation rate. For each of these scenarios, a set of Pareto frontier solutions is obtained. Best solutions show that operating costs could be potentially reduced by 20.9% and that environmental savings could be multiplied by 10 if the recycling supply chain is redesigned. In the same way, customer service could be significantly improved. The SCND model proposed in this case was designed under the sustainable supply chain management paradigm and decisions include strategic and tactical decisions.

1.3.12. IKEA Case Study (Laurin and Fantazy, 2017)

Laurin and Fantazy (2017) present a study in which they identify the best sustainable practices integrated by IKEA in the supply chain. Sustainable best practices concern inbound logistics and outbound logistics:

1. **Inbound logistics:** IKEA has defined a set of rules that must be respected when purchasing products, materials and services called 'IWAY'. This set of rules defines a list of social and environmental requirements that should be respected by suppliers. Requirements include legal requirements such as the respect of laws concerning the Child Labour, Forced Labour, etc. as well as environmental requirements concerning the measuring and the monitoring of energy consumption, the respect of laws concerning GHG emissions, water waste and noise and the treatment of hazardous and non-hazardous materials. In the same way IKEA requires that its first-tier suppliers implement control policies for the second-tier suppliers. In parallel, IKEA has implemented different sustainability policies for procurement. For example, it supports the development of more sustainable technologies for the cotton sourcing.

2. **Outbound logistics:** One of the main contributions of IKEA to implement sustainability for outbound logistics is the use of an innovating "loading ledge" in order to replace the traditional wood pallet. Loading ledges are made of polypropylene, which is an environmental friendly material. Additionally, loading ledges are lighter than wood pallets, which reduces handling costs and transportation CO_2 emissions. Furthermore, its form allows improving trucks capacity usage. Similarly, IKEA produces around 100 millions of copies of their catalogue per year. Hence, a European pulp and paper manufacturer: Svenska Cellulosa Aktiebolaget created a paper for IKEA using post-consumer paper waste, and chlorine-free pulp bleaching process. The use of this paper for the catalogue reduces its environmental impact. Finally, regarding reverse logistics, IKEA implemented a recovery policy for cardboard packaging and furniture.

1.3.13. Conclusion

As a reminder the supply chain addressed in our study is characterized mainly by producing bulky and heavy products, having small production rates, a constrained network configuration and an inbound transportation system managed by suppliers. After reviewing these case studies, we retain the following aspects that may be useful for the our case:

1. MILP models are used in several cases in order to support the SCND process. They are proven to be effective providing guidelines in order to improve supply chains performance.

2. Several case studies evaluate the implementation of intermediary facilities between the sources and the final destinations in order to reduce costs and improve performance.

3. In successful SCND projects the use of simulation and optimization tools must be supported with the participation of all the concerned departments in the company. In occasions, solutions provided by the SCND models are not 100% applicable and must be modified by experts.

4. Sustainability dimension is becoming increasingly important in SCND during the last years. Some studies presented in this section integrate this dimension, and show that some trade-offs can be found in order to improve the profitability of a company and at the same time reduce its environmental impact.

Regarding the case studies conducted in the aeronautic industry, most of them address new challenges faced in this industry related with the early integration of suppliers and the implementation of lean manufacturing practices (Beelaerts van Blokland *et al.*, 2010). In Table 1 we present the study conducted by Ramudhin and Benkaddour (2010). They propose a SCND MILP model that integrates modular conception with sourcing decisions for the supply chain of a jet manufacturer. Tang *et al.* (2013) propose a MILP model that allows locating intermediate processing facilities for a wing box supply chain. In these articles, authors conduct computational experiments using case studies. As a result, models used are proven to work. However, **authors do not provide managerial insights in order to optimize supply chain design in the aeronautic industry** due to the **absence of real industrial data**. Moreover product design (parts assignment to modules) is out of the scope of this study. We focus on inbound flow consolidation and optimization strategies between suppliers and production sites. None of these articles focus on inbound flow optimization strategies.

Challenges faced today by the aeronautic industry concerning inbound SCND have been faced years ago by the automotive industry and other industries. Thus, SCND models developed in these industries could be tailored to the aeronautic industry. Some of the case studies presented here show that important savings could be achieved by optimizing SCND.

To the best of our knowledge there are no published studies focusing on inbound SCND optimizing flow between suppliers and production sites dealing with a real industrial case that allows defining a set of concrete managerial insights in order to reduce logistics costs and improve the environmental impact in the aeronautic industry. Motivated by this gap we conduct the present study.

1.4. AH Supply Chain Network Design

As it is mentioned in the introduction, the main objective of this thesis is to develop optimization and modeling tools that support supply chain design by minimizing total cost (transportation and storage costs) and reducing CO_2 emissions in the aeronautic industry. Hence, we will develop SCND models within two paradigms: lean supply chain management and sustainable supply chain management.

Currently, even if the environmental thinking is becoming increasingly important in the Aeronautic industry, the main driver stills being cost reduction. Hence, in the first stage of this project, we focus on lean SCND models. The aim is to demonstrate the profitability of a SCND project. In the second stage, at the end of the project we integrate the environmental thinking explicitly in the SCND models defined, under the sustainable supply chain paradigm. Particularly, within the framework of a project called design to environment project, AH has set the objective of reducing by 40% the CO_2 for 2030. Thus, the solutions obtained within the sustainable supply chain management paradigm will be presented as a lever of action for the design to environment project.

Concerning the decisions evaluated in this thesis, we will consider only strategic and tactical decisions. The operational level is out of the scope of this thesis. In the second chapter, we characterize the AH supply chain in order to identify the main optimization axes that can be considered in the aeronautic industry or industries with the same characteristics. Based on the optimization axes identified, we define which strategic and tactical decisions are integrated in our SCND models.

2. Current Airbus Supply Chain Analysis and Optimization Axes Identification

As it is mentioned in the introduction, AH has incorporated the modularity concept in its products. Hence, different modules are produced separately in the different Airbus sites: Albacete (Spain), Donauworth (Germany), Marignane (France) and Paris Le Bourget (PLB) (France). The rear fuselage is produced at Albacete, the Airframe is produced at Donauworth, the main rotor and the tail rotor are produced at Marignane and the blades are produced at PLB. Final product assembly takes place at Marignane or Donauworth. Each one of the Airbus sites has its own suppliers; they are located in three different continents: America, Africa and Europe. Hence, there are three type of flows:

I. Inbound flow: Parts flow between suppliers and the different Airbus sites.
II. Inter-Sites flow: Modules and parts flow between the different Airbus sites.
III. Outbound flow: Parts and finished products flow between Airbus and its customers.

In the current supply chain network, suppliers deliver Marignane, Donauworth and Albacete directly as it is shown in Figure 2.1. Concerning parts for PLB, they are first delivered to Marignane and after they are dispatched to PLB grouped with inter-sites flow going from Marignane to PLB (Marignane works as a cross-dock in this case). In the current supply chain, parts are stored at each one of the AH sites.

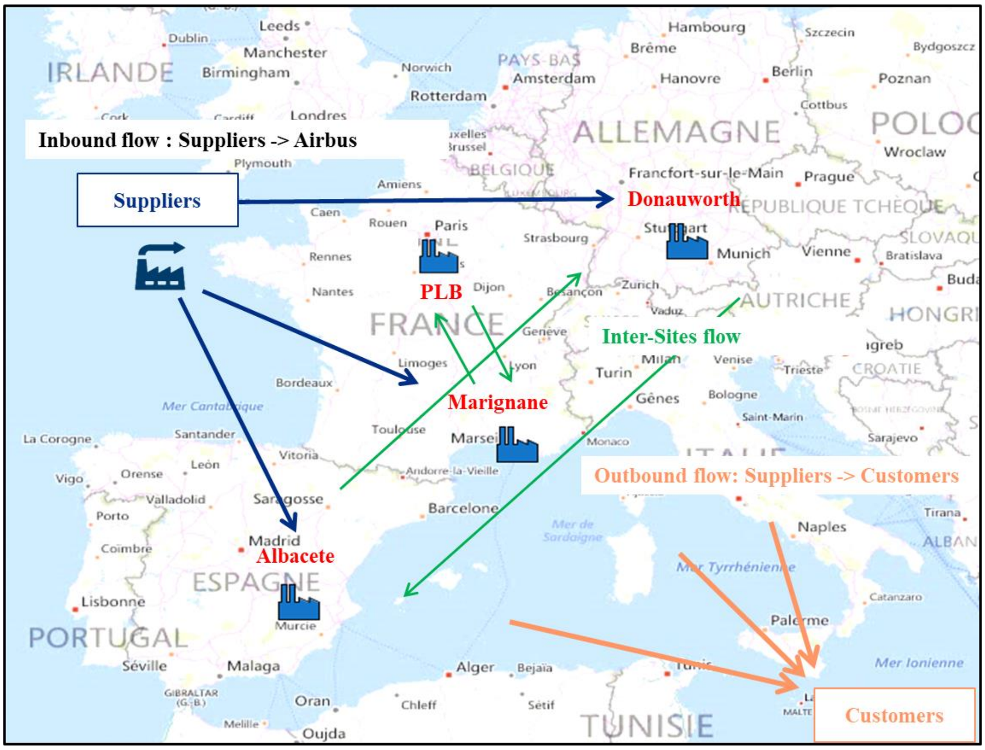

Figure 2.1. Current Supply Chain

In 2018, Airbus launched a project called **Logistics 4.0** in order to transfer all the stock from Marignane and Donauworth to a hub located in Albacete. In other words, in the logistics 4.0 supply chain all the parts coming from suppliers will be stored at a hub located in Albacete. The implementation of the project will take place in 2022. The main driver of this project is surface and labour costs reduction. Concerning flow, in the logistics 4.0 supply chain, the suppliers deliver the hub at Albacete and afterwards, products are delivered to Marignane and Donauworth. Regarding deliveries for PLB, suppliers deliver the hub at Albacete too. Then, products are delivered to Marignane, and afterwards they are dispatched to PLB grouped with inter-sites flow. Logistics 4.0 supply chain network is illustrated in Figure 2.2.

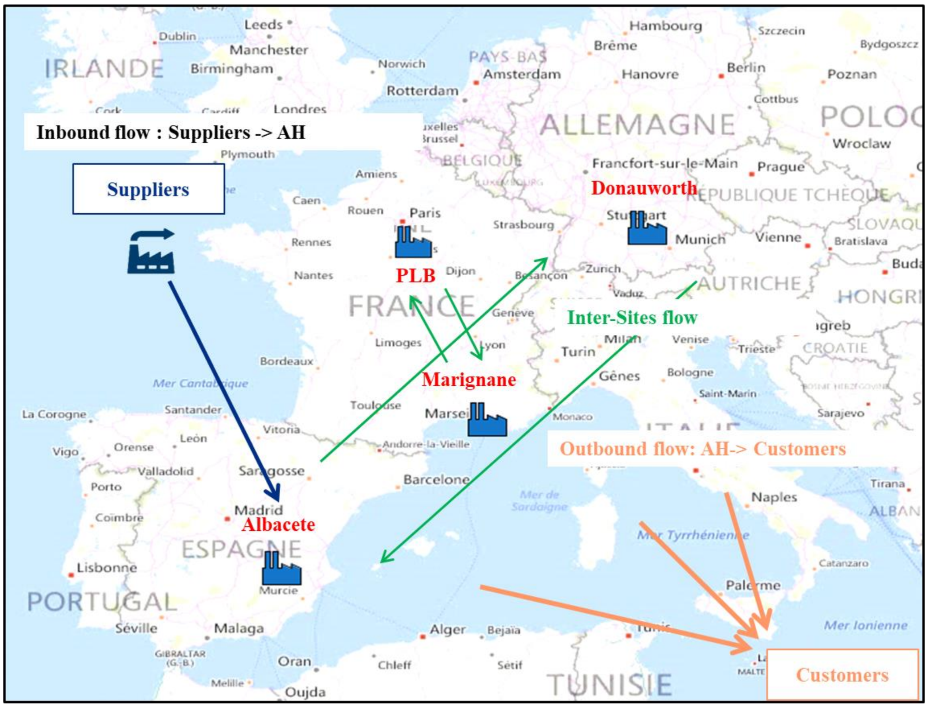

Figure 2.2. Logistics 4.0 Supply Chain

Given that the logistics 4.0 project has been already validated, **in this study we assume that in the current scenario all the suppliers deliver Albacete and we optimize the logistics 4.0 supply chain network. The current supply chain network will be called the old network configuration.**

2.1. Perimeter Definition

This thesis is limited to **inbound flow, or flow between suppliers and Airbus**. We select **a panel of 153 suppliers**, which are representative of product variety, in order to characterize the current inbound supply chain. These suppliers were selected based on parts needed for the assembly of one helicopter. In other words we include all the suppliers of one helicopter. They represent 32% of the turnover of the company. In order to characterize flow and to test the models developed, we use a **database containing deliveries for Marignane and Donauworth for 2018.**

The deliveries database used in this study corresponds to deliveries that took place in 2018 before transferring all the stock to Albacete. However, conclusions obtained with this database apply for the logistics 4.0 supply chain given that the logistics 4.0 project will not modify the procurement policies. Concerning transportation management, it will remain the same. The only modification will be the final destination for the suppliers. Based on results obtained in this study we identified different optimization axes.

2.2. Parts Characterization

The main objective of characterizing parts is to characterize transportation. Weights and volumes are essential parameters in order to define transportation costs and parts cost allow calculating storage costs. For the perimeter defined, suppliers provide 17932 different parts - references. In this section, we characterize them in function of weight, volume and cost.

2.2.1. Weight and Volume

We retrieve parts weight from SAP. From 17932 references, we find weight information for only 11252(63%). Concerning volume, using a database created in 2018 for new references, we retrieve volume for only 225 references over 17932 (1.3%). For references whose weight is missing, we calculate the mean weight per supplier using the information available, and we assume that weight for each reference is equal to the corresponding supplier mean weight. We make this hypothesis taking into account the fact that for 61% of the suppliers, weight standard deviation is equal or less than 1 kilogram.

In the other hand concerning missing volumes, Airbus classifies references in 8 different technology categories: ETIQ, ELEC, COMP, ASSY, META, MTME, MISC and MECA (Table 2.1). At AH, volume and weight information are available only for 542 references (225 are in the perimeter of the study). For these references, mean density per technology is estimated. Then, we classify the 11095 references (62%), whose weight is known and volume is unknown, per technology. We find technology for only for only 4666 references (26% of total). For these references, volume is estimated using mean density per technology. For the rest of the references we use only the weight in this study.

Code EMIC- Technology	Description
META	Metallic parts
COMP	Composite parts
ELEC	Electrical system parts (electrical harness)
ETIQ	Labels
ASSY	Sub-asssemblies
MECA	Mechanical center parts (Machined)
MTME	Structure parts (Machined)
MISC	Various parts

Table 2.1. Codes EMIC-Description

Transportation companies calculate transportation cost based on the maximum between the volumetric weight and the weight. Volumetric weight (kg) is equal to volume in cubic centimeters divided by 5000: transportation companies assume that mean density per pallet is equal to 0.0002 kg/cm^3 (1 divided by 5000). From this point, let us assume that the maximum between the volumetric weight and the weight is called **transport weight**. For references, whose volume is missing transport weight is supposed to be the weight. Transport weight distribution is presented in Figure 2.3.

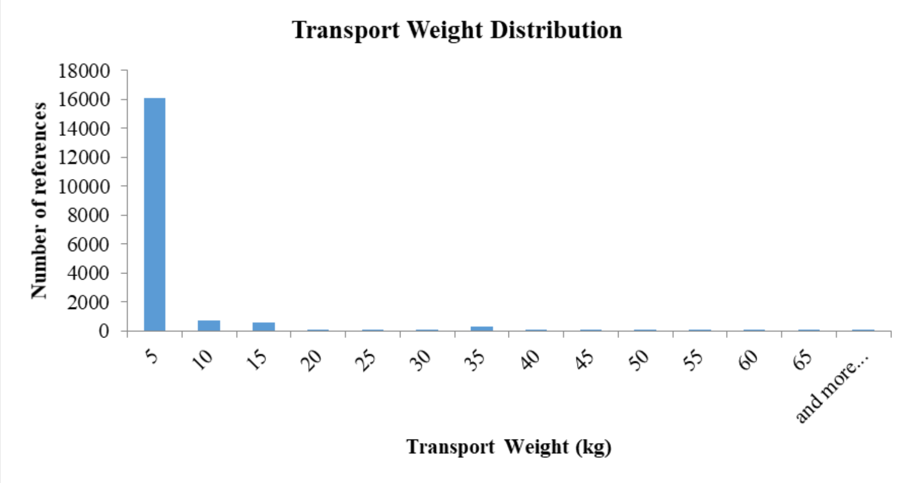

Figure 2.3. Transport weight distribution

For 90% of the references transport weight is less or equal than 5 kg. This is due to the fact that there are a lot of small components as hardware parts (Ex. Screws, nuts, etc.), electrical components, etc.

Finally, given the impact that these strong hypothesis may have on our study, all the results obtained in this chapter were **validated by experts of the AH logistics department**.

2.2.2. Cost

In the same way than weight, we retrieve cost information from SAP. In this case, cost is found for all the references. Figure 2.4 shows parts cost distribution. For 53% of the parts cost is less or equal than 50 €.

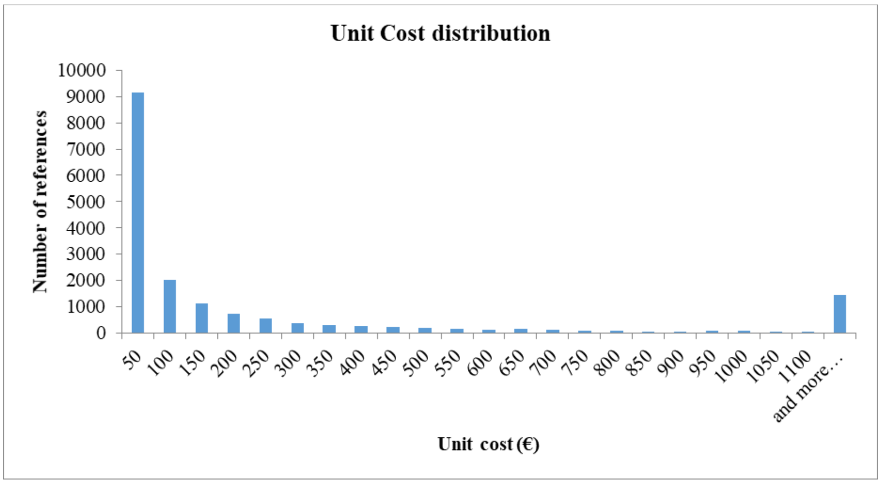

Figure 2.4. Unit cost distribution

2.3. Inbound Flow Characterization

In this section, we characterize inbound flow in function of suppliers' locations, mean delivery frequencies and shipment sizes, delivery methods and transportation modes used, and transportation management.

2.3.1. Suppliers Distribution

Figure 2.5 and Figure 2.6 show suppliers locations for the perimeter defined. They are represented as factories in blue.

Figure 2.5. Suppliers Location

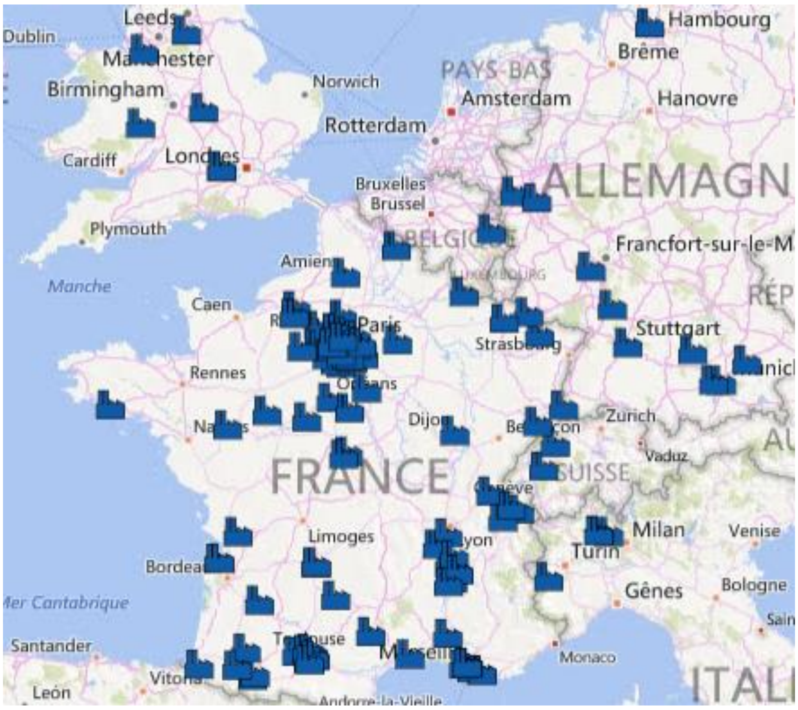

Figure 2.6. Suppliers Distribution – Zoom France

We can see in Figure 2.6 that there are some zones with a high concentration of suppliers, particularly in France. **Suppliers' locations suggest that the location of cross-docking facilities that allow consolidating suppliers' flows must be considered as an optimization axis in this study**. In parallel, we can analyze the implementation of **the milk run transportation concept** around the cross-docking facilities.

2.3.2. Mean Delivery Frequency and Mean Shipment Size

As it is mentioned in Section 2.1, this analysis of the current inbound supply chain is conducted based on 2018 Marignane and Donauworth deliveries for a panel of 153 suppliers. Having this in mind, mean delivery frequency per month is calculated for each couple source destination (248 couples: Suppliers–Marignane, Suppliers–Donauworth). To this end, we estimate the number of shipments for each month per couple source-destination and afterwards we calculate the overall mean of this value for each couple. We build a histogram on mean delivery frequency per month. Results are presented below in Figure 2.7 and Table 2.2.

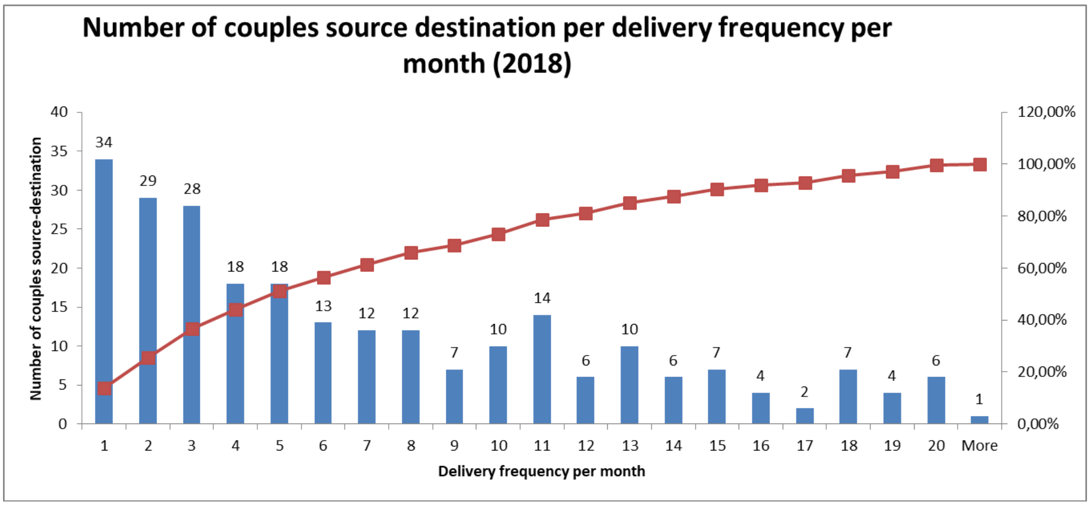

Figure 2.7. Mean delivery frequency per month histogram

Mean delivery rate per month	Number of couples source-destination	%
Once per month or less	34	14%
Twice per month and three times per month	57	23%
Once per week or more	157	63%

Table 2.2. Mean delivery frequency per month distribution

For 63% of couples supplier–site (157 over 248) delivery frequency is equal or bigger than once per week (4 times per month).

In the same way, mean shipment weight is estimated per couple source-destination using the deliveries database and the transport weights estimated in the Section 2.2.1. To this end, we calculate the weight delivered for each shipment for all the couples source-destination based on the references and the quantities delivered. Afterwards, we calculate the overall mean shipment weight for each couple. We build a histogram on mean shipment weight too. Results are presented in Figure 2.8 and Table 2.3.

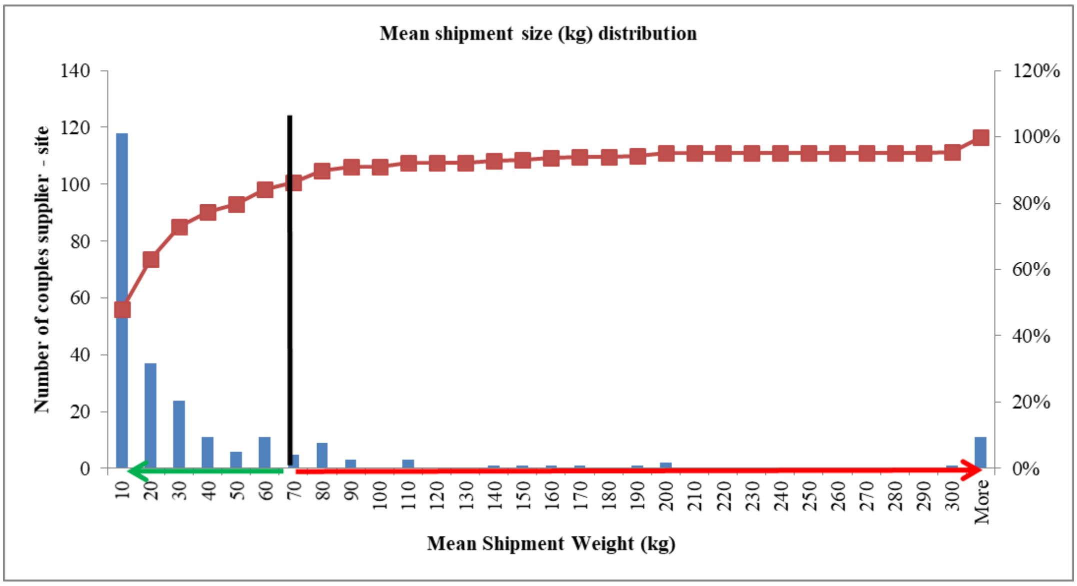

Figure 2.8. Mean shipment weight histogram

Mean (kg)	80
Median (kg)	11
Standard Deviation (kg)	323

Table 2.3. Mean shipment weight distribution

Mean shipment size is smaller than or equal to 70 kg (transport weight limit for parcel and courier services – see Section 2.3.3.) for approximately 86% of couples source - destination.

Finally, in sum, for 39% of couples source - destination mean delivery frequency is bigger than once per week and mean shipment size is smaller than or equal to 35 kg. Taking into account results obtained in this analysis and unit costs distribution presented in Section 2.2, **optimizing transportation lot sizes in function of storage costs and transportation costs per supplier must be considered in this study**.

2.3.3. Delivery Methods and Transportation Modes

In order to identify the delivery methods used by suppliers, we conducted a field study in the Marignane reception zone. As a result, we identified three delivery methods used by suppliers depending on the shipment weight:

- **Parcel and Courier Services (PCS):** Door to door method of delivery. Freight companies suggest using this kind of solution for transport weights smaller than 70 Kg (Freight Center, 2018).

Figure 2.9. Parcel and Courier Services

- **Less than Truck Load solutions (LTL):** These solutions are used when transportation weight is not significant enough to use all the transportation mode capacity. Freight transportation companies suggest using this kind of solutions for transport weights bigger than 70 kg (Freight Center, 2018) and smaller than 11 loading meters (~11 tons, [Projektgruppe Standardbelieferungsformen, 2018]).

Figure 2.10. Less than Truck Load solutions

- **Full Truck Load solutions (FTL):** All the transportation capacity is used. This is the best and cheapest solution for big transport quantities. Transportation companies suggest using this delivery method for transport weights bigger than 11 loading meters (~11 tons, [Projektgruppe Standardbelieferungsformen, 2018]).

Figure 2.11. Full Truck Load solutions

Based on deliveries made in 2018 and assuming that suppliers select the cheapest delivery method for each shipment (given that the delivery method used per shipment is not specified in the file, we estimate PCS, LTL and FTL cost based on the shipment weight for each shipment and we select the cheapest delivery method), we analyze shipments and weight delivered distribution in function of delivery methods. To this end, we calculate the number of shipments and the number of tons delivered per delivery method. Results are presented in Table 2.4. 90% of shipments are delivered using the PCS delivery method, which is coherent with the mean shipment size analysis presented in Section 2.3.2; and 86% of the transport weight delivered is concentrated in 10% of the shipments.

Delivery method	Number of shipments delivered in 2018	% Shipments	Tons Delivered in 2018	% Weight
PCS	15987	90%	239	14%
LTL	1797	10%	1183	68%
FTL	15	0,1%	328	18%
Total	17800	100%	1750	100%

Table 2.4. Shipments and weight delivered distribution in function of delivery methods

Additionally, suppliers use three transportation modes: road freight, sea freight and airfreight. For suppliers located in Europe parts are 100% delivered using road freight. Suppliers located in United States and Canada deliver 100% of their parts using airfreight. There is one supplier located in Mexico: Airbus Mexico. It delivers parts for Marignane using airfreight and parts for Donauworth using sea freight for 80% of the shipments and airfreight for the remaining 20%. Finally, suppliers located in Morocco deliver 100% of their parts using sea freight (Figure 2.12). **Shipments coming from North America by airfreight are delivered using the PCS delivery method.**

Figure 2.12. Transportation modes

As for delivery methods, we analyze the number of shipments and weight delivered distribution in function of transportation modes. Results are presented in Table 2.5.

Transport mode	Number of shipments delivered in 2018	% Shipments	Tons Delivered in 2018	% Weight
Air	1527	9%	83	5%
Road	16225	91%	1687	93%
Sea	48	0,3%	35	2%
Total	17800	100%	1805	100%

Table 2.5. Shipments and weight delivered in function of transportation modes

Sea freight is cheaper and less polluting than airfreight. Sea Freight is already used for one part of the shipments coming from North America (Mexico). Extending the use of sea freight for more shipments coming from North America could lead to logistics costs and CO2 footprint reduction. Furthermore, the use of alternative transportation modes in Europe like rail freight could improve transportation performance too. Hence, **transportation mode selection must be considered in this study taking into account the work in progress (WIP) cost generated due to important lead times in some cases (ex. sea freight lead times).**

2.3.4. Transportation Management

The way in which transportation is managed between each supplier and each Airbus site depends on incoterms defined in the supplier contract. Incoterms are a series of predefined commercial terms published by the International Chamber of Commerce (2020) that are used in commercial transactions and procurement processes. In this case, Incoterms define transportation responsibility for each couple supplier – site.

We retrieve incoterms from SAP for the source-destination couples of this study. Table 2.6 shows the percentage of couples that uses each incoterm, and defines transport responsibility for each one. Table 2.7 summarizes transport responsibility distribution. For 80% supplier – site couples, supplier manages transport, in other words each supplier chooses transportation solutions by its own. **In these cases, Airbus does not have any visibility over transportation costs (they are included in part costs) and inbound logistics operations**. For 20% of the cases, Airbus manages transportation through two transportation providers: Bolloré and Piga. Bolloré delivers international shipments and Piga delivers national shipments. Table 2.8 presents the definition of main incoterms used at AH: DAP, EXW, FCA and DDP.

Incoterm	% couples supplier - site	Transport responsible
DAP	74%	Supplier
EXW	15%	Airbus
FCA	5%	Airbus
DDP	3%	Supplier
FOB	1%	Supplier
CIP	1%	Supplier
CPT	1%	Supplier

Table 2.6. Incoterms distribution

Transport responsible	%
Supplier	80%
Airbus	20%

Table 2.7. Transportation responsibility for suppliers

To go further in our analysis, transportation providers' choice is studied for Marignane site (147 suppliers). We find 39 transportation providers in total and more than approximately a half of suppliers for Marignane use more than one transportation provider to deliver their references. Figure 2.13 and Table 2.9 show suppliers per transportation provider distribution. In order to build Figure 2.13 we take into account the main transportation provider used by each supplier.

The transportation provider most used by suppliers is TNT (23% of suppliers for Marignane use mainly TNT). Today it is hard to understand suppliers transportation providers' choice with the existing databases. However, suppliers were mapped in order to see if there was a relation between transportation provider choice, incoterms and their location. It was found that today there is no relation between them. Figure 2.14 illustrates an example of this situation: We consider three suppliers located in the Parisian region, they have different incoterms and a mean shipment size smaller than 70 kg and they use different transportation providers. **Transportation management needs to be considered in this study.**

Incoterm	Definition
DAP	Delivery At Place Incoterms 2020 It means that the seller delivers when the goods are placed at the disposal of the buyer on the arriving means of transport ready for unloading at the named place of destination. The seller bears all risks involved in bringing the goods to the named place. DAP requires the seller to clear the goods for export.
DDP	Delivery Duty Paid Incoterms 2020, means that the seller assumes all of the responsibility, risk, and costs associated with transporting goods until the buyer receives or transfers them at the destination port. This agreement includes paying for shipping costs, export and import duties, insurance, and any other expenses incurred during shipping to an agreed-upon location in the buyer's country.
EXW	Ex Works Incoterms 2020, means that for the quoted price, the seller/exporter/manufacturer merely makes the goods available to the buyer at the seller's "named place" of business. This trade term places the greatest responsibility on the buyer and minimum obligation on the seller. The seller does not clear the goods for export and does not load the goods onto a truck or other transport vehicle at the named place of departure. The parties to the transaction, however, may stipulate that the seller be responsible for the costs and risks of loading the goods onto a transport vehicle. Such a stipulation must be made within the contract of sale. If the buyer cannot handle export formalities the Ex Works term is not used. In such a case Free Carrier (FCA) is recommended. The Ex Works term is often used when making an initial quotation for the sale of goods. It represents the cost of the goods without any other costs included. Under Incoterms 2020, it is clearly stated that EXW is suitable for domestic trades, where there is no intention at all to export the goods.
FCA	Free Carrier Incoterms 2020 means that the seller delivers the goods to the carrier or another person nominated by the buyer at the seller's premises or another named place. The parties are well advised to specify as clearly as possible the named place of delivery as the risk passes to the buyer at that point. If the named place is the seller facility, the seller is responsible to load the goods. FCA requires the seller to clear the goods for export.

Table 2.8. Incoterms definition (The International Chamber of Commerce, 2020)

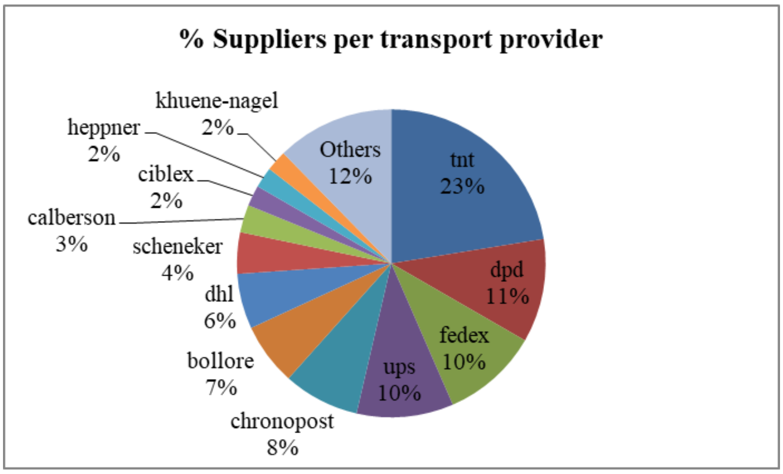

Figure 2.13. Suppliers' distribution per main transportation provider

Number of suppliers per transport provider	
Mean	2,0
Median	2,0
Standard deviation	1,4

Table 2.9. Number of suppliers per transportation provider distribution

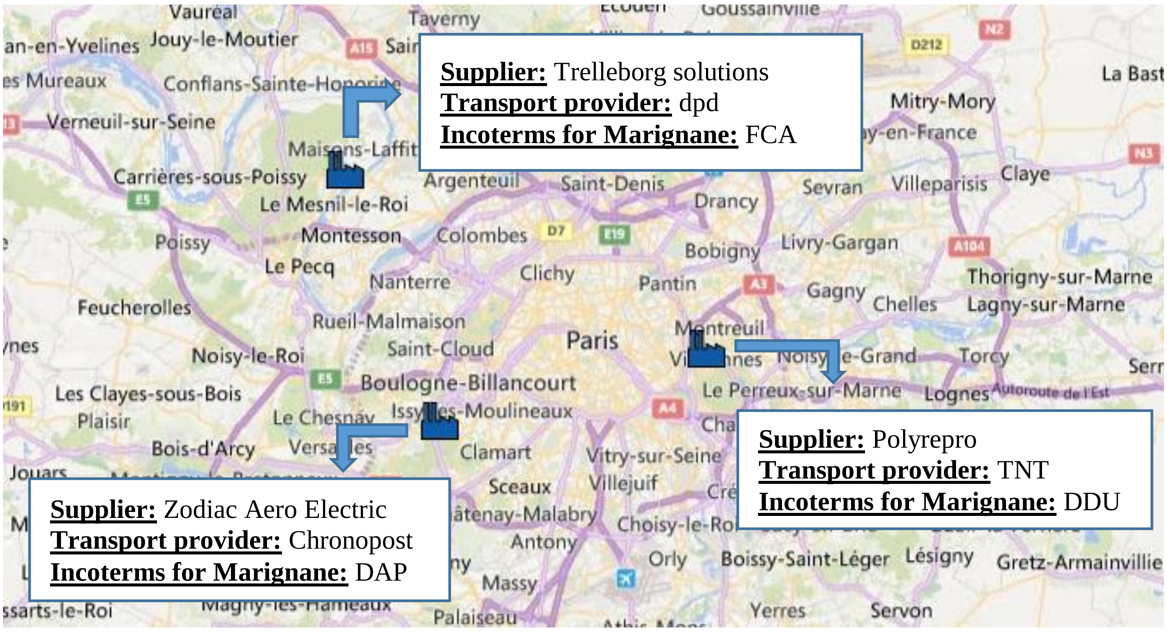

Figure 2.14. Incoterms transportation provider – suppliers mapping

Finally, in the last years, AH started implementing a 4PL concept managed by DHL for new suppliers that integrate its supply chain. A 4PL concept is defined as a transportation management system where "even the management of logistics activities is outsourced. The 4PL (fourth party logistics services provider) focuses entirely on this management task and therefore generally does not own logistics assets" (Cruijssen, 2006). Logistics assets are generally owned by a 3PL (third party logistics service provider), which takes the responsibility of planning and organizing shipments. Incoterms defined in this case are FCA (See table 2.8). This 4PL organization is already implemented for outbound flow.

2.4. Total Cost and CO2 Footprint

In this section, we estimate total transportation cost and CO_2 emissions for the **current scenario**, which assumes the logistics 4.0 supply chain network configuration after transferring the stock to Albacete (in Annex 2, we present a detailed analysis in which we compare cost and CO_2 emissions before and after the implementation of the logistics 4.0 project). From this point we **exclude Safran Helicopter Engines SAS.** This supplier delivers very expensive and bulky parts that are subject to a dedicated transportation mode managed separately.

Total cost and CO_2 emissions estimated in this section will define our **baseline**. In other words, the **current scenario** described in this section will be the basis for estimating potential benefits of the optimization axes addressed in this thesis.

In order to estimate cost and CO_2 emissions we group deliveries going to Marignane and Donauworth the same date coming from the same supplier in one delivery, and we change the final destination to Albacete.

2.4.1. Total Cost

We estimate total transportation cost, storage cost and WIP cost for the current scenario. Concerning transportation cost, it is not known for almost all the suppliers (for 80% of them transportation cost is included in purchasing prices). For that reason, it is necessary to estimate it by defining different hypothesis per delivery method.

- **PCS:** multi-parcel UPS tariffs (UPS, 2018) are used in order to estimate PCS costs. These tariffs are presented as in Table 2.10. Each row corresponds to the shipment weight (transport weight) and each column corresponds to a geographic zone. Geographic zones are defined by UPS according to the shipping distance. The bigger the geographic zone, the longer the distance between the source and the destination.

Tarif des envois multi-colis										
zone	1	2	3	4	5	6	61	7	71	8
Poids										
5 kg	24,70	27,35	30,15	33,15	55,80	76,30	85,25	94,30	103,00	157,95
10 kg	26,80	30,30	33,55	37,15	109,85	133,75	169,45	180,80	194,75	201,60
15 kg	28,90	33,20	37,15	41,50	132,65	162,60	206,15	228,45	239,00	249,95
20 kg	31,10	36,15	41,00	45,65	145,55	178,30	230,30	256,95	268,45	288,85
25 kg	33,30	39,00	44,75	50,25	159,10	195,05	246,50	273,95	291,50	334,05
30 kg	35,55	41,85	48,30	54,30	172,05	210,90	261,75	289,60	313,00	378,10
40 kg	39,40	47,35	55,45	62,00	180,55	224,50	272,80	305,20	328,60	388,75
50 kg	42,75	52,80	62,15	69,60	189,05	238,05	283,90	320,90	343,90	399,40
60 kg	46,55	58,20	69,10	77,20	197,55	251,65	295,00	336,60	359,50	409,75
70 kg	50,25	63,80	76,00	84,95	205,95	265,10	306,10	352,25	374,85	420,45
80 kg	53,85	69,05	82,90	92,40	214,30	278,60	323,70	367,85	390,25	430,90
90 kg	57,45	74,65	89,75	100,10	222,95	292,25	341,40	383,45	405,75	441,50
100 kg	61,00	80,10	96,65	107,65	231,35	305,80	359,10	399,10	421,00	452,15
120 kg	68,65	91,55	110,25	124,60	240,20	323,05	376,80	414,80	453,60	538,65
140 kg	76,30	103,05	123,80	141,45	248,95	340,30	394,40	430,45	486,25	625,35
160 kg	84,15	114,70	137,50	158,30	257,70	357,55	439,20	491,05	555,70	711,85
180 kg	91,65	126,20	150,95	175,25	266,60	374,70	483,75	551,75	625,15	798,25
200 kg	99,40	137,75	164,70	192,15	275,40	392,00	528,60	612,35	694,60	885,00
Plus de 200 kg										
Prix par kg	0,49	0,68	0,82	0,96	1,37	1,96	2,64	3,06	3,47	4,42
Prix min	99,40	137,75	164,70	192,15	275,40	392,00	528,60	612,35	694,60	885,00

Table 2.10. Multi-parcel UPS tariffs

Transportation cost is given for multiples of 5 kg until 25 kg, for multiples of 10 between 30 kg and 100 kg and for multiples of 20 between 100 kg and 200 kg. In order to estimate transportation cost in-between each interval (0-5kg, 5 -10kg, etc.), we define a linear cost function per interval based on upper and lower bounds. We take this decision based on UPS mono-parcel tariffs (see Table 2.11), in this case costs are presented for weights between 1 kg and 5 kg and between 5 kg and 10 kg. We make a linear regression for each interval and we find that it is a good approximation for costs in-between these intervals (Determination coefficient > 0.98 for all the geographic zones). In this case quantity discounts are taken into account implicitly when using the UPS cost matrix.

Tarif des envois mono-colis										
zone	1	2	3	4	5	6	61	7	71	8
EUR										
Poids										
1 kg	15,20	18,10	19,70	20,00	33,20	46,50	63,55	73,75	84,90	105,25
2 kg	16,00	19,05	21,20	21,60	37,35	52,35	67,75	76,15	90,80	122,15
3 kg	16,90	20,20	22,75	23,10	41,70	57,95	72,05	78,70	94,75	133,15
4 kg	17,65	21,25	24,20	24,55	46,00	63,90	76,40	81,10	98,75	143,95
5 kg	18,60	22,30	25,85	26,10	50,10	69,70	80,70	84,00	102,45	154,70
6 kg	19,35	23,70	27,15	27,55	59,95	80,75	93,25	105,00	119,50	163,35
7 kg	20,35	25,20	28,45	29,05	69,70	91,90	105,55	126,35	136,55	171,95
8 kg	21,25	26,60	29,80	30,55	79,60	103,10	117,90	144,15	153,50	180,60
9 kg	22,10	28,10	31,05	32,05	89,20	114,20	130,40	161,85	170,55	189,25
10 kg	22,95	29,55	32,30	33,50	99,05	125,40	142,95	179,55	187,55	197,95

Table 2.11. Mono-parcel UPS tariffs

- **LTL Tariffs:** LTL tariffs per pallet are estimated based on a DHL quotation tool (DHL, 2018). For France (71% of the suppliers are located there) one tariff is retrieved and transportation cost per pallet for each couple supplier-site is calculated on a pro rata basis in accordance with the shipping distance. For suppliers of other countries only one tariff per pallet is retrieved for each country and the same tariff is used for all suppliers located in that country. Transportation cost per pallet is assumed to be linear. It means that the cost of shipping two pallets is supposed to be equal to two times the cost of shipping one pallet. It is assumed that each pallet has a capacity of 1000 kg (transport weight - European pallet – 120 cm x 80 cm). For sea freight LTL shipments, tariffs are retrieved from iContainers (2018). In this case we do not take into account quantity discounts. However, these hypothesis as well as cost estimation were validated by the logistics department, which means that the approach used allows obtaining a good approximation of transportation cost.

- **FTL Tariffs:** Currently Daher (logistics services provider) manages inter-site transportation for Airbus. Based on Daher tariffs and DHL quotations, FTL cost for each couple supplier-site is calculated on a pro rata basis in accordance with the shipping distance. In the same way, it is assumed that the cost per FTL shipment is linear, in other words, the cost of two FTL shipments (ex. two truck shuttles) is equal to two times the cost of one FTL shipment. For sea freight FTL shipments, tariffs are retrieved from iContainers (2018).

It is assumed that suppliers select for each shipment the minimum cost delivery method respecting transportation mode constraints.

Concerning the storage cost only capital cost is taken into account. At Airbus it is assumed in 2018 to be equal to 10% of parts cost. As it was mentioned previously transportation cost is included in parts cost, however based on figures provided by the purchasing department, transportation cost corresponds to 0.6% of parts cost on average which may no impact significantly storage costs.

Generally, storage costs include other costs related to materials handling, rent, risk costs and other costs associated with surface and labour costs. This could lead to storage costs bigger than 10%. However, in this study we suppose that labour and surface costs are fixed regardless the shipment sizes: the warehouse surface and the number of employees in charge of storage and handling operations are fixed. Even if an increase in the mean inventory level may increase the surface required in the warehouse, this increase would be negligible due to small delivery volumes treated in this study (1750 tons delivered per year). Moreover, based on figures provided by the logistics department, taking into account mean electricity costs per square meter in France (Selectra, 2020), and assuming that we can put one pallet (1000 kg) per m², the estimated surface cost per kg (including energy cost and rent cost) at the warehouse is only 0.09 € per m² per kg per year. The only storage cost included in order to compare the different scenarios that will be presented in the next chapters will be the capital cost (10% of parts cost), which varies in function of the shipment sizes.

In order to estimate storage cost per year, based on the data file containing deliveries for 2018 we estimate the mean shipment size per supplier and we assume that mean stock level is equal to mean shipment size divided by 2. In reality, mean stock level could be greater than mean shipment size divided by 2 if we include security stock. Later on Chapter 5, we will conduct a sensitivity analysis on storage costs.

For shipments coming from Mexico by sea freight, transportation delay is not negligible. For that reason, it is necessary to estimate the WIP cost for these shipments. To this end, we use the Little's Law:

$$\text{WIP cost} = \text{Throughput} * \text{Lead Time} * 10\% * \text{parts cost} \tag{2.1}$$

It is assumed that sea freight lead-time is equal to 18 days for shipments coming from North America based on different transportation cost quotations made online (iContainers, 2018). Throughput is estimated based on demand per year per supplier.

Transportation Cost, Storage Cost and WIP Cost are estimated based on the database containing deliveries for 2018 mentioned previously. Resulting total costs for the **current scenario** are presented in Table 2.12.

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Total Cost per year
Current scenario	154 K€	99 K€	3,03 M€	**3,3 M€**

Table 2.12. Total Cost Current Scenario

2.4.2. Transportation CO_2 Footprint

In order to estimate transportation CO_2 emissions we use the method proposed by Mathers *et al.* (2014) in The Green Freight Handbook:

$$\text{Greenhouse Gas Emissions} = D*W*EF. \quad (2.2)$$

Where D is the distance the shipment has travelled, W is the weight of the shipment and EF the transportation mode's specific emission factor. Emission factors are coefficients that allow converting activity data into CO_2 emissions. In the case of transportation activities, they are usually presented in gr of CO_2 per ton-km. Emissions factors depend on several aspects as the capacity use rate, the kilometers of empty running and the size of the transportation mode. The higher is the capacity use rate, the smaller is the emission factor. The smaller is the number of kilometers of empty running, the smaller is the emission factor as well (McKinnon and Piecyk, 2011). For transportation modes included in this study, we define different hypothesis concerning these aspects. They are presented in Table 2.13. **The FTL emission factor will be used in Chapters 4, 5 and 6 for shipments for which a truck's capacity use rate of 90% or higher could be ensured.**

Mode	Emission Factor (gr CO2/ton.km)	Hypothesis
Road PCS/LTL	272	Emission factor for LTL and PCS delivery methods are retrieved from the ADEME web site (Agence de l'Environnement et de la Maîtrise de l'Energie). This factor takes into account the fact that in France for PCS and LTL services mean capacity use rate is 25% in France, including empty running. (Bilans GES ADEME, 2019a)
Road FTL	75	Concerning FTL delivery method it is assumed that mean capacity use rate is 90% and that truck comes back to the source after delivering the parts: 50% of empty running. Emission factor for this hypothesis is retrieved from a report made by the Logistics Research Centre of the Heriot-Watt University in Edinburgh. (McKinnon and Piecyk, 2011). **We will use this emission factor for FTL shipments where capacity use rate is bigger or equal than 90% .**
Air Freight	946	We assume that Airplanes used for North America shipments have a capacity bigger than 250 passengers and that mean distance traveled is between 6000 and 7000 kms. Emission factor in this case is retrieved from the ADEME website too. (Bilans GES ADEME, 2019a)
Sea Freight	29	In case of sea freight, it is assumed that we used a container ship of less than 1200 TEU (Twenty foot equivalent). Emission factor is retrieved from the ADEME website as well. (Bilans GES ADEME, 2019a)

Table 2.13. Emission Factors

Using the emission factors defined per transportation mode, transportation CO_2 footprint is calculated for the perimeter of the study. Tons of CO_2 emitted per year as well as total weight delivered per transportation mode are presented in Table 2.14 for the **current scenario**.

Current Scenario Transportation Carbon Emissions				
Transport Mode	**Tons delivered (2018)**	**% Weight**	**Tons CO2 emitted (2018)**	**% CO2**
Air	65	4%	580	**45%**
Road	1632	93%	688	**55%**
Sea	53	3%	10	**1%**
Total	**1750**	**100%**	**1277**	**100%**

Table 2.14. CO_2 emissions current scenario

Results show that even if only 4% of the volume is delivered using airfreight, it produces 45% of CO_2 emissions. Hence replacing airfreight shipments by sea freight shipments could reduce significantly CO_2 emissions.

2.4.3. Analysis per Country

Based on results obtained in the previous sections, we evaluate weight delivered and transportation cost per country for the current scenario:

Country	Tons Delivered	% Weight	Transportation Cost	% Cost
France	1597	91,3%	1938 K€	70,5%
Mexico	83	4,8%	235 K€	8,5%
United States	24	1,4%	241 K€	8,8%
Germany	20	1,1%	128 K€	4,6%
Canada	6	0,3%	60 K€	2,2%
Great Britain	2	0,1%	50 K€	1,8%
Italy	6	0,3%	26 K€	0,9%
Morocco	5	0,3%	24 K€	0,9%
Switzerland	1	0,1%	17 K€	0,6%
Austria	3	0,2%	15 K€	0,6%
Belgium	3	0,2%	14 K€	0,5%

Table 2.15. Tons delivered and transportation cost per country

As it is shown in Table 2.15, most of the volume delivered and transportation cost is concentrated in France, Mexico and United States. Hence, the possibility of installing cross-docking facilities in order to consolidate suppliers' shipments in France and North America must be studied.

2.5. Conclusion

In this chapter, we described the current AH supply chain. Based on a database containing deliveries for 2018 for a panel of 153 suppliers, we characterize products and inbound flow for the current scenario. This database is representative of the AH current situation. As a result, we identify four optimization axes: **1) Transportation lot sizing, 2) Transportation mode selection, 3) Cross-Docks location and 4) Milk run implementation**. In Chapters 3 and 4 we propose different optimization models per axis of optimization. These models are evaluated using Airbus instances and they are after used in Chapter 5 in order to build an optimized transport solution for AH under the lean supply chain management paradigm.

In the same way, we estimate total cost and CO_2 emissions for the current scenario which assumes the logistics 4.0 network configuration. We exclude **Safran Helicopter Engines SAS** as it delivers very expensive and bulky parts that are subject to a dedicated transportation mode managed separately. In this way the total cost obtained for the **current scenario** is **3.3M€** per year. Regarding CO_2 emissions, **1277 tons of CO_2** are emitted per year in the **current scenario**. This is our **baseline.** Optimized scenarios in the next chapters will be compared with this scenario.

As it was shown in this Chapter, one of the main characteristics of the AH supply chain is that transportation is managed by suppliers. Hence, there is no visibility over transportation operations. This results on a supply chain that is not optimized as a whole. Additionally, due to the fact that transportation is managed by suppliers, procurement policies are defined only in function of storage costs, which results in small shipment sizes and big delivery frequencies: for 39% of couples source - destination mean delivery frequency is bigger than once per week and mean shipment size is smaller than or equal to 35 kg. Table 2.16 summarizes the main AH inbound supply chain main characteristics.

AH Inbound Supply Chain Characteristics	
Transportation management	In 80% of the cases, suppliers manage transportation. There's no visibility over transportation operations.
Mean delivery frequency	In 63% of the cases, delivery frequency is bigger than or equal to once per week.
Mean shipment weight	In 86% of the cases, mean shipment weight is smaller than or equal to 70 kg.
Total volume delivered per year	Suppliers included in this study deliver 1750 tons per year.
Transportation modes	Three transportation modes are used: road freight, sea freight and air freight. Air freight is prioritized for oversea shipments. Road freight is the norm for continental shipments.
Delivery Methods	Three delivery methods are used: Parcel and Courier Services (PCS) for 90% of the shipments, Less than Truck Load (LTL) for 9.9% of the shipments and Full Truck Load (FTL) for 0.1% of the shipments.

Table 2.16. AH Inbound supply chain main characteristics

In several companies in the aeronautic industry transport is managed by suppliers, resulting in supply chains with characteristics that are similar to the AH supply chain. For example, Roy and Elias (2018) analysed international logistics management in the Canadian Aeronautic Industry. They evaluate transport management for 16 companies in the aeronautic industry. Results show that in 63% of the cases suppliers manage inbound transportation. Moreover, based on some benchmarking analysis conducted by AH, in other companies in the aeronautic industry as Leonardo, transportation seems to be managed by suppliers. Thus, the optimization axes identified for the Airbus case can be applied to other companies in the aeronautic industry with similar characteristics. In order to optimize the inbound supply chain, it is necessary to implement a transportation organization that allows having control and visibility over transportation operations. According to some benchmarking analysis conducted by AH, some companies in the aeronautic industry as Bell seems to have already an inbound transportation organization where they manage and control transportation operations.

3. Transportation Lot Sizing and Mode Selection

In this chapter, we study transportation lot sizing and transportation mode selection optimization axes identified before.

1. **Transportation lot sizing:** Currently AH defines procurement policies in function of storage costs only, which results in big delivery frequencies and small transportation lot sizes, as it is shown in Chapter 2**.** For this reason in this section, we study the possibility of defining optimized transportation lot sizes in function of transportation and storage costs. A model is developed in order to optimize the transportation lot sizes for PCS, LTL and FTL costs structures presented in Chapter 2. This model is applied to the Airbus case.

2. **Transportation mode selection:** Currently suppliers use three transportation modes: road freight, sea freight and airfreight. For suppliers located in Europe parts are 100% delivered using road freight. Suppliers located in United States and Canada deliver 100% of their parts using airfreight and the supplier located in Mexico delivers its parts using airfreight and sea freight. Sea freight can be cheaper and is less polluting than the other transportation modes. For that reason, we propose to study the possibility of extending the use of sea freight as an alternative for all the suppliers located in North America. To this end, a transportation mode selection model is developed taking into account infrastructure requirements. After, this model is used in a case study conducted for shipments coming from North America to Albacete.

The optimization axes studied in this chapter do not modify the supply chain network *i.e.* no location decisions are included.

3.1. Transportation Lot Sizing

Currently at AH, for the perimeter of the study, 80% of suppliers manage transportation by their own, and AH does not have visibility over transportation costs; they are included in the part prices. In other words, total transportation cost paid by Airbus does not depend on delivery frequencies in appearance. Hence Airbus define replenishment policies that minimize only inventory costs, without taking into account transportation costs which leads to big delivery frequencies and small shipment sizes as it was shown in Section 2.3.2. For the remaining 20% of suppliers, even if transportation is managed by Airbus through different transport providers, replenishment policies are defined in the same way. In that context, defining transportation responsibility is a critical decision in Supply Chain Management, particularly in inbound logistics management. In one hand, by giving suppliers the responsibility of managing transport operations, a company could release transportation tasks resources for the company core activity. However, in some cases, this could mean losing control over transportation and procurement policies because of the lack of transparency and visibility in transportation management and costs. In the other hand, by internalizing transportation management, a company has total control over its transportation system, and hence, it could optimize transportation and procurement policies by defining optimal transportation lot sizes and delivery frequencies in function of transportation and storage costs. The main disadvantage in this case is that the company needs to allocate resources for the transportation management task.

A common approach used for defining optimal transportation lot sizes in literature, is the classic economic lot size model introduced at first by Harris in 1913 (Harris, reprint 1990) and after developed by Wilson in 1934. This model allows estimating optimal order quantities in function of order and storage costs. We adapt this approach to the Airbus case and we evaluate two scenarios. 1) Current scenario: this is the Airbus current scenario presented in Chapter 2 in which transportation lot sizes are determined only in function of storage costs. 2) Orders grouping scenario: Airbus implements a transportation organization that allows having full visibility over transportation costs and it optimizes transportation lot sizes based on storage and transportation costs for all the suppliers. In order to evaluate the second scenario we develop a transportation lot-sizing model adapted to PCS, LTL and FTL cost structures presented in Chapter 2.

In the next section, we present a state of the art for the transportation lot sizing problem. Afterwards, we present the transportation lot-sizing model developed based on literature and with PCS, LTL and FTL cost structures. Then, we present the Airbus case study and the main results obtained for the scenarios defined.

3.1.1. Literature Review

Determining optimal inventory management policies is essential in order to optimize supply chain costs. There is a very extensive literature dealing with the inventory management problem. Inventory management models can be classified based on the parameters behaviour (deterministic or stochastic), the number of periods included (single period or multiple periods), the number of products (single product or multiple products) and the number supply chain stages at which inventory decisions are taken (Saha and Ray, 2019). Chen and Hu (2012) develop a single product deterministic inventory management model where order quantities and prices are defined simultaneously at the beginning of each period based on holding costs and ordering costs. In their model there is a price adjustment cost each time that price is modified. Rossi *et al.* (2015) study a multi-period stochastic inventory management problem in which demand at each period depends on a probability function. To this end they develop a unified MILP modelling approach. O'Neill and Sani (2018) propose a deterministic single product inventory management model in which demand rate is determined by price and deterioration is taken into account for stored items. The model proposed allows defining optimal order quantities maximizing profit. There are also models that integrate inventory management with other supply chain decisions. Wu *et al.* (2021) study a location-inventory-routing problem. In this problem there is a supply chain composed of multiple potential distribution centers and retailers. Retailers demand is deterministic. Parts are stored at the retailers and at the distribution centers. The objective is to define the optimal location of distribution centers, replenishment policies and vehicle routing. The authors propose a two-stage hybrid meta-heuristic algorithm to solve the problem.

In this Section, taking into account the strategic and tactical nature of our study, we deal with a single period and single product problem. Our objective is to define optimal transportation lot sizes between suppliers and their destination based on deterministic storage costs, transportation costs and demand. Moreover, only transportation lot sizes need to be optimized in our problem (other SCND decisions are excluded). For these reasons, we will focus on the classic Economic Order Quantity (EOQ) model as it is the most appropriate for the Airbus case.

The EOQ model is a commonly used approach that allows obtaining orders quantities that minimize ordering and storage costs. Let us assume that there is a retailer, which faces a constant demand per unit of time D for a determined item. This retailer must place orders for this item to another facility. It fixes order quantities at Q units per order. The retailer must pay a fixed ordering cost K every time he places an order and storage cost per unit held in inventory per unit of time is h. Given these assumptions, we can define the economic order quantity (Q*) that minimizes ordering and storage costs as (see for example Simchi-levi *et al.*, 2014):

$$Q^* = \sqrt{\frac{2KD}{h}} \tag{3.1}$$

The classic EOQ makes several assumptions: 1) demand is constant and continuous, 2) order sizes are not limited by the storage capacity, 3) holding costs per unit do not depend on total quantity held in stock and 4) ordering costs do not depend on the order size. The EOQ model is frequently criticized because of its applicability to real industrial cases and the difficulties to estimate its parameters. However, this model has been proven to be good enough to help companies to reduce their logistics costs, and its implementation costs are negligible compared to its potential benefits (Drake and Marley, 2014).

There are many variants of the EOQ model, which have evolved over time. Salameh and Jaber (2000) propose an EOQ model adapted for items with imperfect quality. To this end, they define a percentage of defective products received per lot. These items should be identified and treated separately. Pentico and Drake (2011) conduct a survey on EOQ models including partial backordering, which occurs when products in stock are not enough to satisfy the customer demand. Even if the first version of the EOQ model was proposed by Harris in 1913, extensions of the EOQ model that have been developed during the last years are countless. Some of these extensions integrate the sustainability dimension in the EOQ model. In these cases, social and environmental impacts are associated with the inventory holding and ordering operations (Bouchery *et al.*, 2012).

In this study, we are interested particularly in the EOQ extensions that include transportation costs. Blumenfeld *et al.* (1985) are one of the first who extend the EOQ formula to the case of the point-to-point transportation. In this case, they calculate the EOQ taking into account the inventory at the origin and the destination and the in-transit inventory. Instead of defining a fixed ordering cost, they define a fixed freight charge per shipment. After they define the optimal shipment size as the minimum between the optimal given by the EOQ formula and the capacity of the transportation mean. Later Lee (1986) extends the EOQ model in order to include freight costs quantity discounts. In this case, he defines a set up cost function S(Q) per shipment as follows:

$$S(Q) = F_i + A, if\ N_{i-1} < Q \leq N_i\ i = 1,2,\dots,I. \tag{3.2}$$

Where Q is the amount of each order, F_i is the freight cost for shipment sizes Q between N_{i-1} and N_i and A is a fixed cost. In this case, the author uses the EOQ formula to estimate a Q_i per interval. Afterwards he develops an algorithm to find the optimal Q that yields the minimum cost over all the intervals. Swenseth and Godfrey (2002) define a model for FTL (Full Truck Load) and LTL (Less than Truck Load) shipment methods for transportation costs with quantity discounts. Concerning the LTL tariffs, they assume a variable cost per pound with quantity discounts. The model proposed allows obtaining the optimal Q* taking into account both shipment methods. Abad and Aggarwal (2005) propose a model that allows defining the optimal reselling price and transportation lot size for a reseller. Jaruphongsa *et al.* (2007) consider a two stage lot-sizing model. This model provides an optimal replenishment plan for a warehouse (first stage) and an optimal delivery plan from the warehouse to a distribution center (second stage). For a further literature on EOQ extensions the reader can refer to Meyer (2015), Rieksts and Ventura (2008) and or Drake and Marley (2014).

Nowadays the EOQ model is a tool very often used to solve industrial transportation lot sizing problems or in general order lot sizing problems, especially in the automotive industry. Blumenfeld *et al.* (1987) develop an EOQ tool for point-to-point transportation for General Motors: TRANSPART. They apply it at first at General Motors' Delco Electronics Division showing a 26% logistics costs saving opportunity. The automotive industry has a fast increasing demand and very important productions rates (Ex. Approximately 13000 cars per day at Toyota). Therefore, in this industry the EOQ model is a very convenient tool to optimize inventory management policies. In this study, we will evaluate the implementation of this method in the Aeronautic Industry, which in contrast has small demand and low production rates (Ex: <500 units per year).

3.1.2. PCS, LTL and FTL Transportation Lot Sizing Model

We develop a model based on transportation lot sizing literature to estimate optimal transportation lot sizes for FTL, LTL and PCS transportation cost structures defined before. To this end, we assume that time horizon is infinite, due to products range renewal small frequency (less than once each ten years per product), and that production rates are constant, given that AH smooth production due to industrial constraints. We do not include order costs; we consider they do not depend on the number of deliveries. Order costs correspond to procurement staff labour costs. Currently, procurement policies are characterized by big delivery frequencies and small shipment sizes. With our model, it expected that delivery frequencies decrease, which means that fewer orders will be placed. Even if the reduction of the number of orders placed is significant, we are not considering additional savings like reducing the procurement staff in our study. We calculate optimal transportation lot sizes in kilograms (multi-products) using an approach per interval similar to the one used by Lee (1986). Quantity discounts are taken into account for PCS costs implicitly, based on UPS tariffs presented in Section 2.4.1.

As we mentioned it in Section 2.4.1, we assume that UPS (PCS) costs are described by a linear function per interval for each geographic zone:

$$UPS\ cost_i(Q) = Cv_iQ + Cc_i \qquad if\ L_i < Q \leq U_i \tag{3.3}$$

Where Q is the shipment weight, Cc_i represents the intercept (constant cost), Cv_i represents the slope (variable cost per kg), L_i is the lower bound of the interval and U_i is the upper bound of the interval. We note Cs the storage cost per kg per year, D the volume delivered in kg per year and T the time interval between deliveries (in years) in which we consume Q. Then the total cost TC_i per shipment for a given interval is:

$$TC_i(Q) = Cv_iQ + Cc_i + Cs\frac{Q}{2}T \qquad if\ L_i < Q \leq U_i \tag{3.4}$$

Given that T is equal to $\frac{Q}{D}$, total cost per shipment can be written as:

$$TC_i(Q) = Cv_iQ + Cc_i + Cs\frac{Q^2}{2D} \qquad if\ L_i < Q \leq U_i \tag{3.5}$$

If we divide TC by Q, we obtain the total cost per kilogram $TC\ per\ kg_i$:

$$TC\ per\ kg_i(Q) = Cv_i + \frac{Cc_i}{Q} + Cs\frac{Q}{2D} \qquad if\ L_i < Q \leq U_i \tag{3.6}$$

$TC\ per\ kg_i$ is a convex function, hence we can find the Q_i^* that minimizes the total cost TC_i for the interval i which corresponds to the EOQ:

$$Q_i^* = \sqrt{\frac{2DCc_i}{Cs}} \qquad if\ L_i < Q \leq U_i \tag{3.7}$$

Concerning the LTL costs, given that it is assumed that cost per pallet is linear and that a pallet has a capacity of 1000 kg, transportation cost is constant for weights between 0 and 1000 kg (Cost of one pallet), 1000 kg and 2000 kg (Cost of 2 pallets), and so on. Consequently, we calculate the Q_i^* per interval using the EOQ formula too, by replacing Cc_i with the corresponding LTL cost C_{LTLi} of the interval. In other words, C_{LTL1} is the cost of shipping one pallet if 0 kg < Q ≤ 1000 kg, C_{LTL2} is the cost shipping two pallets if 1000 kg < Q ≤ 2000 kg and so on.

$$Q_i^* = \sqrt{\frac{2DC_{LTLi}}{Cs}} \qquad if\ L_i < Q \leq U_i \tag{3.8}$$

Concerning FTL costs, assuming that the truck/container capacity is equal to 24000 kg, transportation cost is constant for weights between 0 and 24000 kg (Cost of one FTL shipment), 24000 kg and 48000 kg (Cost of two FTL shipments) and so on. As for LTL costs, we calculate the Q_i^* per interval using the EOQ formula replacing Cc_i with the corresponding FTL cost C_{FTLi}.

$$Q_i^* = \sqrt{\frac{2DC_{FTLi}}{Cs}} \qquad if\ L_i < Q \leq U_i \tag{3.9}$$

When calculating the Q_i^* for each interval i for the PCS, LTL and FTL cases, it is necessary to take into account the interval bounds. If the Q_i^* is less than or equal to the lower bound L_i of the interval, the Q_i^* for the interval must be equal to the lower bound L_i. Similarly, if the Q_i^* is greater than or equal to the upper bound U_i of the interval, the Q_i^* for the interval must be equal to the upper bound U_i. To illustrate this situation, let us see an example in Figure 3.1. There are two total cost curves: the first one (blue) for a transportation cost of 100 and the second one for a transportation cost of 300 (red). The first curve corresponds to the total cost function for weights between 0 and 40 kg (dotted over the second interval) and the second curve corresponds to the total cost function for weights between 40 and 80 kg (dotted over the first interval). The Q_i^* optimal for the first interval, corresponds to the optimal (EOQ) of the first curve (blue), which is in the first interval, and then it is not necessary to modify it. In contrast, the Q_i^* optimal for the second interval is 40 kg (lower bound of the interval), given that the optimal (EOQ) of the second curve (red) is less than 40 kg.

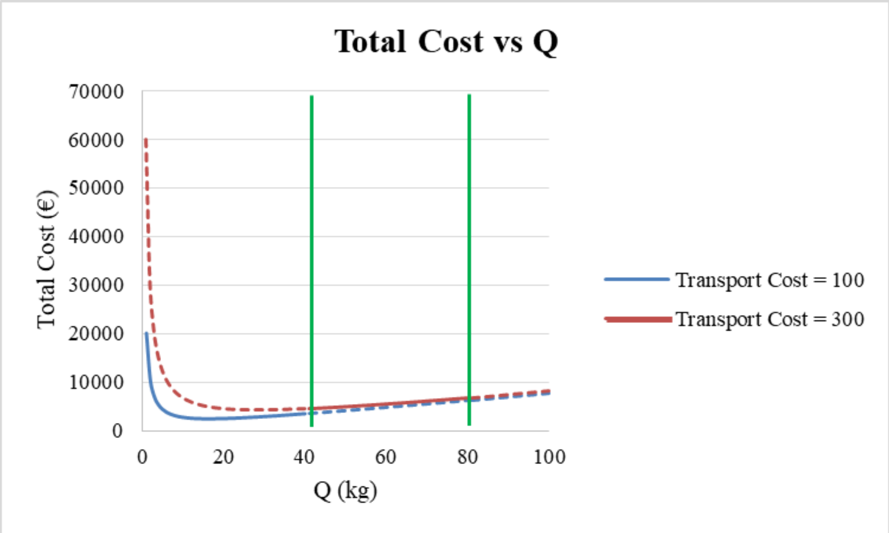

Figure 3.1. Total cost curves per interval – Example

We calculate the Q_i^* for all the intervals for each delivery method. Afterwards we select the Q_i^* and the delivery method (PCS, LTL or FTL) that minimize the total cost per supplier. These Q_i^* are traduced after into optimal delivery frequencies. In order to obtain more realistic results we approximate these delivery frequencies to industrial delivery frequencies frequently used defined in Table 3.1. Storage and transportation costs are recalculated in function of the industrial frequencies obtained.

Industrial delivery frequencies	Shipments per year
Once each 6 months	2
Once each 3 months	4
Once each 2 months	6
Once per month	12
Twice per month	24
Once per week	48
Twice per week	96
Three times per week	144
Once per day	240

Table 3.1. Industrial delivery frequencies

When calculating the optimal transportation lot size, it is necessary to take into account transportation mode constraints for each supplier. In cases where a supplier uses more than one transportation mode, the cheapest transportation mode is selected.

Finally, in this model optimal shipment sizes are calculate in kilograms. Hence, Cs is estimated using mean storage cost per kg per supplier. We make this assumption taking into account that cost per kg variance is not significant for suppliers delivering multiple components.

3.1.3. Airbus Case Study

As we mentioned it before, we evaluate two transportation scenarios at Airbus Helicopters:

1. **Current scenario**: In this scenario, 80% of suppliers manage transportation by their own, and Airbus does not have visibility over transportation costs; they are included in the part prices. In other words, total transportation cost paid by Airbus does not depend on delivery frequencies in appearance. Hence, Airbus defines replenishment policies that minimize only inventory costs, without taking into account transportation costs, which leads to big delivery frequencies and small shipment sizes. For the remaining 20% of suppliers, even if Airbus manages transportation through different transport providers, replenishment policies are defined in the same way, without taking into account transportation costs. This scenario corresponds to the current supply chain described in Chapter 2. Total cost for this scenario is already estimated and is presented at the beginning of this chapter.

2. **Orders grouping scenario:** Airbus implements a transportation organization that allows having full visibility over transportation costs. It optimizes transportation lot sizes based on transportation and storage costs. To evaluate this scenario, we use the transportation lot sizing model presented previously.

Total costs and CO_2 footprint for the current and the optimized scenario are presented in Table 3.2.

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Total Cost per year	% Cost Reduction	Tons CO2 Emitted per year	% CO2 Reduction
Current scenario	154 K€	99 K€	3,03 M€	3,3 M€	-	1277	-
Orders grouping scenario	592 K€	118 K€	1,27 M€	1,98 M€	**-40%**	966	**-24%**

Table 3.2. Transportation lot sizing model results

By optimizing transportation lot sizes in function of transportation costs and storage cost, total cost could be potentially reduced by 40% compared to the current scenario. As expected, cost reduction achieved is mainly due to a reduction of the delivery frequencies (increase of the transportation lot sizes). For 99% of suppliers (150 over 152 suppliers) delivery frequency is reduced. For the remaining 1%, delivery frequency increase. The number of suppliers per delivery frequency per year is presented in Figure 3.2 for the current and the orders grouping scenario. In the current scenario 76% of the suppliers, deliver Albacete twice per week (96 times per year) or more, while in the orders grouping scenario 86% of the suppliers deliver Albacete twice per month (24 times per year) or less.

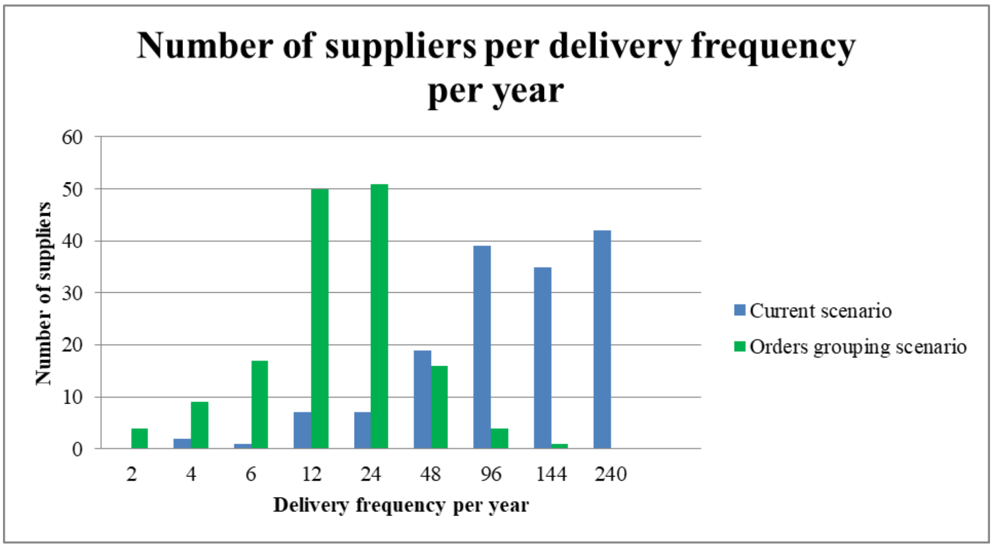

Figure 3.2. Suppliers per delivery frequency per year distribution

Regarding the CO_2 footprint, it is reduced by 24%. When optimizing transportation lot sizes only a transportation mode and a delivery method is selected per supplier. Hence, all the shipments coming from Airbus Mexico are delivered using sea freight in the orders grouping scenario, which reduces CO_2 footprint significantly compared to the current scenario. Tables 3.3 and 3.4 show CO_2 emissions and weight delivered distribution per transportation mode for the current scenario and the orders grouping scenario. Compared to the current scenario, in the orders grouping scenario, airfreight emissions are reduced and sea freight emissions are increased due to the use of sea freight instead of airfreight for all the shipments coming from Mexico. Similarly, road freight emissions increase due to additional road transportation between Airbus Mexico and the respective seaports.

Current Scenario Carbon Emissions				
Transport Mode	**Tons delivered (2018)**	**% Weight**	**Tons CO2 emitted (2018)**	**% CO2**
Air	65	4%	580	**45%**
Road	1632	93%	688	**54%**
Sea	53	3%	10	**1%**
Total	**1750**	**100%**	**1277**	**100%**

Table 3.3. Current Scenario CO_2 emissions and weight delivered per transportation mode

Orders Grouping Scenario Carbon Emissions				
Transport Mode	**Tons Delivered per year**	**% Weight**	**Tons CO2 emitted per year**	**% CO2**
Air	30	2%	221	23%
Road	1632	93%	729	75%
Sea	89	5%	17	2%
Total	**1750**	**100%**	**966**	**100%**

Table 3.4. Orders Grouping Scenario CO_2 emissions and weight delivered per transportation mode

3.1.4. Conclusion

Today, at AH 80% of suppliers manage transportation; in these cases, transportation cost is unknown for Airbus. For the remaining 20%, Airbus manages transportation through different transportation providers. In both cases, the replenishment policies are defined only in function of storage costs, which leads to big delivery frequencies and small transportation lot sizes.

In this section, we study the transport lot-sizing optimization axis. To this end, we evaluate two scenarios. The first scenario is the "current scenario". The second one is named the "orders grouping scenario". In this scenario, Airbus implements a transportation organization in which we assume it has visibility over transportation costs and optimizes transportation lot sizes in function of storage and transportation costs.

In order to evaluate the second scenario we develop a transportation lot sizing model for PCS, LTL and FTL cost structures based on the literature. This model is based on the principles of the classic economic lot size model introduced at first by Harris in 1913 (Harris, 1990).

Using the model developed, we optimize the current scenario and determine logistics costs and CO_2 emissions for the orders grouping scenario. As a result, total cost is reduced by 40%, and CO_2 footprint is reduced by 24% in the orders grouping scenario compared to the current scenario. As expected in the orders grouping scenario, delivery frequency is reduced for 99% of the suppliers compared to the current scenario. Moreover, in the current scenario, approximately 42% of Mexico's volume is delivered using airfreight and the other 58% using sea freight. In the orders grouping scenario 100% of Mexico's volume is delivered using sea freight, which leads to CO_2 emissions reduction.

Finally, for AH and for companies in the aeronautic industry with an inbound transportation management system similar to the AH one (See Table 2.16 in Chapter 2), it is recommendable to implement a transportation organization in which there is visibility over transportation costs (*i.e.* modify the incoterms) and to redefine replenishment policies in function of transportation and storage costs. It is necessary to take into account that the optimal transportation lot sizes obtained with the model proposed should be evaluated by the procurement department. In some cases, these quantities could be modified in function of procurement constraints (suppliers' contractual terms).

3.2. Transportation mode selection

Currently mainly three transportation modes are used by suppliers to deliver parts to Airbus: road freight, sea freight, and airfreight. For the perimeter of the study, shipments coming from Europe are delivered using road freight, shipments coming from United States and Canada are delivered using airfreight and shipments coming from Morocco are delivered using sea freight. Concerning Mexico, shipments going to Marignane are delivered using airfreight and shipments going to Donauworth are 80% delivered using sea freight and 20% delivered using airfreight. Shipments delivered using airfreight are delivered using only the PCS method and shipments delivered using sea freight are delivered using the FTL and LTL delivery methods. Concerning road freight PCS, LTL and FTL delivery methods are used.

In the current transportation management system (see Section 2.3.4.), suppliers manage transportation by their own in 80% of the cases, and there is no visibility over transportation operations. Hence, currently at AH, the logistics department do not know if transportation mode choice is optimized. Moreover, with the current transportation system, products are damaged frequently due to transportation conditions, given that suppliers select in some cases transportation providers that are not trained to respect the aeronautic industry constraints.

Sea freight mode can be cheaper and is much less polluting than airfreight, thus in this context, it is appropriate to study the possibility of including sea freight as an alternative transportation mode for all the suppliers located in North America, and not only for Airbus Mexico as in the current situation. In the next section, we present a state of the art of transportation mode selection, afterwards we develop a transportation mode selection model for our case. Then, we study the inclusion of sea freight as an alternative for all the AH North America shipments, and finally we present the results of the case study and the conclusions.

3.2.1. Literature Review

Transportation represents an important part of logistics costs. According to Russell and Taylor (2003) transportation accounts for 20% of total logistics costs on average. For that reason, selecting transportation modes and carriers for moving goods or products is a critical decision in transportation cost optimization. Transportation mode selection decision is often based on cost and lead time. However, during the last years, with globalization of markets, the apparition of Just In Time (JIT) policies, an increasingly demanding market as well as the integration of sustainability dimension in logistics management, transportation mode and carrier selection is becoming increasingly complex.

There are many studies dealing with transportation mode and carrier selection. According to Meixell and Norbis (2008) they can be classified in three categories: attributes identification, decision process development and supply chain integration.

3.2.1.1. Attributes Identification

This category groups studies focusing on the identification of the different attributes evaluated by shippers when they select a transportation mode or carrier within different contexts. As it was mentioned before, the most basic attributes evaluated when selecting a carrier are cost and delay. However, attributes that are more complex could be evaluated depending on the context.

Attributes evaluated when selecting carriers variate in function of carrier-shipper relationships. Attributes evaluated in long-term alliances may be different from factors evaluated in traditional transactional-based shipments. Lu (2003) provides a study in order to identify the main factors that influence shippers' satisfaction in partnerships with carriers. To this end, he conducts a survey in which 30 service attributes are evaluated. The five most important attributes identified are availability of cargo space, low damage or loss record, accurate documentation, reliability of advertised sailing schedules and courtesy of inquiry. Attributes are after grouped in 8 factors. Results show that time related services factor has the most important impact in shippers' satisfaction. Williams *et al.* (2013) conduct a study in order to identify main selection attributes for less than truck load shippers. To this end, firstly, based on literature they identify the most frequently used key attributes. After using a LinkedIn discussion group between shippers and carriers, they validate the list of attributes defined. Then, using a Delphi method and maximum difference scaling, they develop a survey instrument. This instrument allows collecting data from a business research panel. As a result the four main attributes identified are: respect of delivery dates, respect of pick up dates, competitive rates and transit time.

Similarly, with the emergence of global markets, carrier attributes taken into account by shippers start varying between national and international markets. In international markets transportation modes alternatives are reduced and shipments require more paper work and may include freight forwarders. Semeijn (1995) conducts a study involving 305 international shippers and 27 global carriers. The three most important attributes identified for international shipments are reliability, transit time and cost. Danielis *et al.* (2005) present a study that identifies main attributes evaluated by logistics managers in an international environment. Results obtained show that international shippers prioritize quality attributes over costs attributes and hence they are willing to pay higher rates in order to ensure that quality is not deteriorated. Another increasingly important attribute in international markets is transportation flexibility. Naim *et al.* (2006) define transportation flexibility in function of internal flexibility capabilities, for example, the ability to provide different types of freight vehicles, and external flexibility capabilities, for example the ability to redefine the services provided.

Finally, during the last years, with the growing importance of environmental protection and social commitment, sustainability attributes start being integrated in transportation mode and carrier selection. Fan *et al.* (2018) conduct a review in order to highlight the importance of taking into account greenhouse gases (GHG) emissions when evaluating transportation modes. Davis-Sramek *et al.* (2018) conduct a study in order to evaluate the relative importance of the economic, sustainable and social dimension in carriers' selection. To this end they use behavioral decision theory to analyze data collected from a set of scenario based experiments conducted for different samples of supply chain managers. Results show that the economical dimension dominates the sustainable and the social dimension. Davis-Sramek *et al.* (2020) study the influence of environmental and social sustainability performance in carriers' selection. In this study they conduct two scenario-based experiments. The first scenario is characterized by a long term arrangement between shippers and carriers and the second scenario is characterized by a short term arrangement between them. Results show that the environmental performance of the carrier dominates the social sustainability performance in long term arrangements.

3.2.1.2. Decision Process Development

There exists a variety of qualitative and quantitative models for transportation mode and carrier selection. The first approaches used in carrier selection are cost-based models. McGinnis (1989) classifies transportation mode choice models in four categories: the first category refers to classic economic models where distance break-points are defined per transportation mode from which another transportation mode becomes a better alternative. The second category concerns inventory-theoretic models, which define the best transportation alternative based on inventory, ordering and transportation costs. The third category groups trade-off models, in this case, modes are compared based on the sum between transportation and non-transportation costs. The last category groups constrained optimization models in which the objective is to minimize transportation costs subject to non-transportation costs constraints. These models take into account the fact that some non-transportation costs as the service level are not quantifiable. Liberatore and Miller (1995) propose to use the Analytic Hierarchy Process (AHP) model for transportation mode and carrier selection. This model define a set of criterions; in the case studied by Liberatore and Miller (1995) criterions defined include perceived quality, EDI capabilities and potential to develop long-term partnership. For each of the criterions a weight is defined based on pairwise comparison. Finally, each of the alternatives is scored for each of the criterions and the best alternative is selected based on the weighted sum of the scores. Garrido and Leva (2004) propose a multi-nomial probit model applied to a port and carrier selection case for Chilean fruit exporters. This model is a statistical model that allows identifying the most likely outcome based on probabilities defined for a set of variables. In the case of Garrido and Leva (2004), an utility function is defined per port-carrier alternative. Then, for each one of the alternatives, it is estimated the probability of having a bigger utility than the rest of alternatives. Results show that carrier selection depends on port selection. Lin and Yeh (2010) study carrier selection for stochastic logistics networks. In their study, a performance index is developed for logistics networks reliability. It is defined as the probability that d units are successfully delivered to a customer. They develop a genetic algorithm in order to determine the optimal logistics network with the maximum performance index in order to select carriers.

In the last years, sustainability criteria has been integrated in transportation mode and carrier selection models. Most of the models used to evaluate transportation environmental impact estimate CO_2 emissions or GHG emissions per transportation mode. Fan *et al.* (2018) group assessment methods used to evaluate transportation environmental impact in two categories: cost-based models and impact-weighting models. Cost-based models translate impact into monetary terms. For example by defining a penalty (€) per kg of CO_2 emitted. Impact-weighting models define an impact weight per transportation mode based on transportation mode emissions. Most of the models that integrate the sustainability dimension are supply chain design models where transportation mode choice is part of the decision variables evaluated in the model. These models are discussed next.

3.2.1.3. Supply Chain Integration

In practice, transportation mode selection is evaluated in conjunction with other supply chain optimization decisions. Miller and Matta (2003) propose a model that integrates transportation and production scheduling decisions. To this end, they develop a MILP model, which minimizes production-associated costs as well as transportation costs. Different freight rates are defined for different transportation modes. Liao and Rittscher (2007) propose a non-linear mixed integer combinatorial optimization model that integrates supplier selection, procurement lot sizing and carrier selection decisions. The objective of the model is to minimize total logistics costs, rejected items and late deliveries. It defines different transit times and costs for each carrier alternative.

As it was presented in Chapter 1, transportation mode and carrier selection makes part of tactical decisions evaluated in supply chain design. Hence, many supply chain design studies propose models integrating transportation mode decisions. Carlsson and Rönnqvist (2005) conduct a case study on Södra, one of the largest Swedish forest companies. They describe five supply chain planning optimization projects. These projects involve procurement, production, distribution planning and transportation mode selection. Transportation modes are defined in function of network requirements (capacity, service level, etc.). Cordeau *et al.* (2006) propose a MILP for a logistics network design problem. This model includes decision variables concerning the location of plants and warehouses, products flow and transportation modes. The only criterion evaluated for transportation modes is cost in this case. Wilhelm *et al.* (2005) provide a MILP model to design supply chain assembly systems under the North American Free Trade Agreement (NAFTA). This model integrates facility location, flow between facilities and transportation mode decisions. Transportation modes are evaluated in function of cost and capacity requirements.

Finally, there exists also supply chain models integrating the environmental impact of transportation modes. Fareeduddin *et al.* (2015) propose a supply chain network design (SCND) model for a closed-loop supply chain. Transportation modes evaluated include sea freight, road freight and rail freight. For each transportation mode, an emission factor is defined. Three carbon emissions policies are evaluated: carbon cap, carbon tax, cap-and-trade (see Section 1.1.3.). Martí *et al.* (2015) propose a SCND model for a responsive supply chain with stochastic demand. In this case, airfreight, sea freight, rail freight and road freight are evaluated. For each one of the modes it is defined the cost, the speed, the lead-time and the energy consumption in kilograms of fuel per ton and per kilometer. Emissions are estimated in function of fuel consumption and a cost is defined in function of market fuel price. Two carbon policies are evaluated: carbon tax and carbon cap. Rezaee *et al.* (2015) propose a green SCND model that incorporates uncertainty to carbon price. In this case, different costs and CO_2 emissions are defined for a set of transportation modes. Concerning the carbon price, different probability functions are tested. In general, sustainable SCND models including transportation mode selection decisions, define different emission or energy consumption factors and costs per transportation mode. To go further on these models the reader can refer to Waltho *et al.* (2019).

Based on literature, we can identify mainly five transportation modes: road freight, airfreight, sea freight, waterways freight and rail freight. They are briefly described in Table 3.5. Rail freight, sea freight, waterways freight and airfreight are often combined with road freight. This is called intermodal transportation; it is defined as a "multimodal transportation of goods, in one and the same intermodal transportation unit by successive modes of transportation without handling of the goods themselves when changing modes." (European Conference of Ministers of Transport *et al.*, 1997). Intermodal transportation allows taking profit of the advantages of each transportation mode and allows reducing costs and the environmental impact in some cases.

Transportation mode	Description	CO2 emissions
Road Transportation	It is the most commonly used transportation mode. It is very cost-effective and allows door-to-door delivery. It is very flexible in terms of the variety of services proposed.	Emissions factors for road freight depend on the type of vehicle used, the capacity use rate and the kilometers of empty running (Mckinnon and Piecyk, 2011). Generally, road freight is less polluting than airfreight and more polluting than rail freight and sea and waterways freight.
Air Transportation	It is a quick transit and reliable transportation mode. Lead-times are much smaller than sea freight lead-times. It requires important landing and take-off areas. Hence, it is often combined with road freight to deliver the final destinations. It is generally the most expensive transportation mode.	Emission factors depend on the capacity of the airplane, the capacity use rate and the distance traveled (Bilans GES ADEME, 2019a). It's the most polluting transportation mode.
Sea and Waterways Transportation	It is used for long-distance shipments. It allows carrying large volumes (i.e. The equivalent of 10 semi-trailer trucks). Thanks to the use of containers, it is suitable for a large range of products. Transportation costs per unit of weight are the lowest because of large carrying volumes. However, it has the biggest lead times. It is often combined with road freight to deliver the final destination.	It is much less polluting than road freight and airfreight. Similarly, emission factors depend on transportation capacity and capacity use rate. (Bilans GES ADEME, 2019a)
Rail Transportation	When delivering bulky shipments over long distances, rail freight offers an appropiate solution. Lead times are smaller than road freight lead times. However, it is not as flexible as road freight (i.e. infrastructure requirements). It is often combined with road freight to deliver the final destination.	It is less polluting than airfreight and road freight. Emission factors depend on transportation capacity and capacity use rate. (Bilans GES ADEME, 2019a) Electric rail freight is less polluting than waterways freight.

Table 3.5. Transportation modes

3.2.2. Transportation Mode Selection Model

We develop a simple cost-based transportation mode selection model taking into account infrastructure constraints. Given that we are not taking into account carriers (*i.e.* DHL vs UPS), we do not evaluate service attributes. Furthermore, the objective of this study is to identify a set of guidelines at a strategic and tactical level in order to reduce costs and CO_2 emissions. Sustainability dimension will be most deeply investigated in the last chapter. Hence, we only focus on cost reduction in this chapter. Our model is composed by two steps:

1) **Infrastructure requirements:** For each shipment taking into account infrastructure constraints, we define the set of possible transportation mode alternatives. For example, transportation modes such as sea freight require seaports to be near of the source and the destination, or rail freight requires a railway connecting the source and the destination.

2) **Cost estimation:** For each one of the transportation modes defined we estimate transportation costs based on shipment weights for each delivery method. The transportation mode and delivery method with the minimum cost is selected for each shipment.

3.2.3. Airbus Case Study

As it is mentioned at the beginning of this chapter, at AH there are mainly three transportation modes used by the suppliers included in this study: airfreight, sea freight and road freight. Shipments delivered using airfreight use the PCS method; shipments delivered using sea freight use FTL and LTL delivery methods; shipments delivered using road freight use FTL, LTL and PCS delivery methods.

Concerning suppliers located in Europe, currently all the shipments are delivered by road freight. In these cases, the use of rail freight could be studied only if it is combined with other transportation modes. However, rail freight is appropriate for long distances and important volumes and volumes delivered by suppliers are very small. Hence, intermodal transportation for these suppliers is not included in this chapter. According to figures provided by DHL intermodal road-rail transportation and road transportation have the same cost but rail-road solutions are less polluting. Hence, rail-road solutions will be considered later in Chapter 6 when combining cross-dock location and transportation mode selection axes in order to reduce CO_2 emissions (the use of cross-docking facilities facilitate the consolidation of small shipments in FTL shipments, intermodal transportation from this grouping points to Albacete can be considered). For the supplier located in Morocco, transportation mode is already optimized. Sea freight is the cheapest and the less polluting transportation alternative.

In this case study, we consider extending the use of sea freight as an alternative for all the suppliers located in North America. In order to reduce the complexity of the problem and due to information availability constraints (there is no information at AH about tariffs proposed by sea freight shippers) we define the following assumptions concerning transportation costs:

1. LTL and FTL sea freight tariffs are retrieved from iContainers (2018) for shipments between the port of New York, USA and the port of Valencia, Spain (near to Albacete). We assume all the suppliers that use sea freight in North America deliver the port at New York and that sea freight transportation cost is the same for all of them. It is assumed that all the sea freight shipments arrive to the port of Valencia and afterwards they are transported to Albacete.

2. It is necessary to use road freight in order to transport parts from suppliers to the port at New York and from the port of Valencia to Albacete. In this case, in order to estimate road transportation cost, we use LTL and FTL tariffs estimated based on distance using the DHL quotation tool (DHL, 2018) and Daher tariffs.

3. Based on quotations made on iContainers(2018) we assume that lead time for sea freight shipments is equal to 18 days

Taking into account these assumptions, we apply the model presented before to shipments coming from North America in 2018 in order to compare two scenarios:

1. **The current scenario:** This scenario corresponds to the current situation where only Airbus Mexico uses sea freight and airfreight. The rest of the suppliers located in North America use only airfreight.

2. **The Sea freight inclusion scenario:** In this scenario, we apply the transportation mode selection model presented previously to suppliers located in North America. In other words, in this scenario, suppliers select the cheapest transportation mode between airfreight and sea freight for each shipment in 2018. Work in progress (WIP) cost is included for sea freight due to important lead times.

Total costs and CO_2 emissions per year are presented for both scenarios in Table 3.6.

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Total Cost per year	% Cost Reduction	Tons CO2 Emitted per year	% CO2 Reduction
Current scenario	154 K€	99 K€	3,03 M€	**3,3 M€**	**-**	**1277**	**-**
Sea freight inclusion	154 K€	115 K€	2,94 M€	**3,2 M€**	**2%**	**988**	**23%**

Table 3.6. Sea inclusion for all North America suppliers' results

As it is shown in Table 3.6, total cost is reduced by only 2% in the sea freight inclusion scenario compared to the current scenario. This is due to the fact that in the sea freight inclusion scenario volume delivered using sea freight instead of airfreight increase only by 34 tons which represents 2% of the total volume (1750 tons: Europe, North America and Morocco). Conversely, CO_2 emissions are reduced by 23% in the sea freight inclusion scenario compared to the current scenario due to the big difference between the sea freight emission factor and the airfreight emission factor (see Section 2.4.2.). Tables 3.7 and 3.8 show weight delivered and CO_2 emissions repartition for the current scenario and the sea freight inclusion scenario respectively for Canada, Mexico and United States. Emissions produced by road freight transportation from the suppliers to the seaport at New York and from the port of Valencia to Albacete are included. With the inclusion of sea freight as an alternative for all the shipments, 92% of the weight delivered by Mexico is shipped using sea freight in the sea freight inclusion scenario compared to 57% in the current scenario. Similarly, 20% and 14% of volume coming from Canada and United States respectively is delivered using sea freight in the sea freight inclusion scenario. For the rest of the shipments airfreight is the cheapest alternative taking into account storage cost, WIP cost and transportation cost.

Current scenario weight and CO2 repartition - MEX, CA and USA					
Region	**Transporation mode**	**Weight delivered per year (tonnes)**	**% Weight**	**Tons CO2 emitted**	**% CO2**
Canada	**Air**	6	5%	37	6%
Mexico	**Air**	35	31%	359	56%
	Sea + Road	48	43%	67	10%
United States	**Air**	24	21%	183	28%
Total		**113**	**100%**	**646**	**100%**

Table 3.7. MEX, US and CA weight and CO_2 emissions reparation – Current scenario

Sea freight for all scenario weight and CO2 repartition - MEX, CA and USA					
Region	**Transporation mode**	**Weight delivered per year (tonnes)**	**% Weight**	**Tons CO2 emitted**	**% CO2**
Canada	**Air**	5	4%	30	8%
	Sea + Road	1	1%	0,5	0,1%
Mexico	**Air**	6	5%	62	17%
	Sea + Road	77	69%	107	30%
United States	**Air**	20	18%	156	44%
	Sea + Road	4	3%	3	1%
Total		**113**	**100%**	**357**	**100%**

Table 3.8. MEX, US and CA weight and CO_2 emissions reparation – Sea freight inclusion scenario

3.2.4. Conclusion

In this section, we study transportation mode selection optimization axis. We conduct a comprehensive literature review on transportation mode and carrier selection. Models reviewed vary in function of the attributes evaluated (cost, lead-time, service level, etc.) and the approach used (quantitative/qualitative).

In this chapter, we focus on cost reduction. Hence for the AH case, we propose a very simple cost-based transportation mode selection model. We use this approach in order to evaluate the possibility of using sea freight as an alternative for all the shipments coming from North America. As a result, in the sea freight inclusion scenario total cost is reduced by 2% and CO_2 emissions are reduced by 23% compared to the current scenario. Hence sea freight is a cost-efficient and sustainable transportation mode alternative in some cases.

Based on results obtained in this chapter, it is recommendable for AH and companies with a similar transportation management system (See Table 2.16 in Chapter 2), to modify the transportation organization in order to have more control over transport operations and optimize transportation mode choice.

Finally, in this chapter we do not study intermodal transportation for suppliers in Europe. This alternative will be studied in Chapter 6 in conjunction with cross-docks location in order to reduce CO_2 emissions.

4. Cross-Dock Location and Milk Run Concept Evaluation

After analysing suppliers' location in section 2.3.1., we have found that there are some regions with a high density of suppliers. This analysis suggests that the implementation of cross-docking facilities must be considered in this study. In parallel, we can consider the implementation of the milk run concept around these facilities. Cross-docking facilities and milk runs are solutions that allow consolidating LTL and PCS shipments in FTL shipments (LTL, FTL and PCS delivery methods are defined in Section 2.3.3.), which can potentially reduce costs. Both of these axes require the modification of the supply chain network.

In the current supply chain, 80% of the suppliers manage transportation by their own, separately and there is no visibility over transportation operations for AH (see Section 2.3.4.). Hence, within the current transportation management system, it is complicated to optimize inbound flow with consolidation strategies at a strategic level. In order to implement such strategies, it would be necessary to modify the current transportation organization in order to have control over all the inbound flow. **In this chapter, we assume that in the scenarios where cross-docking and milk run strategies are implemented the current transportation organization is modified in order to have control over all the inbound flows.**

In the next sections, we develop a cross-dock location and a milk run evaluation model based on the literature. Then, we apply them to an AH instance.

4.1. Cross-Dock Location

As it was shown in chapter 2, in the current supply chain, there are different geographic zones such as France with an important concentration of suppliers. This distribution suggests that the implementation of consolidation strategies such as cross docking can be considered in this study.

In the first part of this section, we present a literature review on cross-docking strategy and facility location models. Afterwards we develop a first cross-dock location model for AH and we apply it to the 2018 shipments file used in the previous chapters. Based on results, we develop an improved version of the model and we apply this new version to the AH instance. Finally, we analyse the results obtained and we present the conclusion.

4.1.1. Literature Review

Cross-docking is a logistics strategy very often used by companies in order to optimize supply chain networks. Main goals of cross-docking are costs reduction, shipments consolidation and lead times reduction. Belle *et al.* (2012) define cross-docking as "the process of consolidating freight with the same destination (but coming from several origins), with minimal handling and with little or no storage between unloading and loading of the goods". In that way, the main difference between cross-docking facilities and the traditional warehousing – distribution centers, is the fact that in cross-docking facilities products are temporally stored for a small amount of time. In literature, some authors define 24 hours as the storage time limit in cross-docking facilities (Vahdani and Zandieh, 2010). However, in some companies, even if products are stored for a longer time, they still considering logistics platforms as cross-docks as long as "products move from supplier to storage to customer virtually untouched except for truck loading"(Belle *et al*., 2012).

Compared to point-to-point transportation the main advantages of cross-docking are: transportation costs reduction, consolidation of shipments and improved resource utilization. By locating cross-docks, several LTL shipments can be consolidated in an FTL shipment. In this way, transportation cost is reduced due to LTL transportation distances reduction and truck capacity use rate is improved through the consolidation of LTL shipments in a FTL shipment. We can find some successful cases of cross-docking implementation as the Toyota Case (Rechtin, 2001) and the Walt Mart Case (Stalk *et al.*, 1992). According to Belle *et al.* (2012), mainly two factors can influence the suitability of a cross-docking strategy in a company: demand stability and unit stock out costs. Cross-docking is a good alternative when demand is stable and unit stock-out costs are low. If unit stock-out costs are important, cross-docking stills being a good solution if it is supported by appropriate planning tools and information systems. Furthermore, cross-docking potential benefits increase if distance between suppliers and their destinations is important.

In this section, we are particularly interested in determining the optimal location of cross-docking facilities within a supply chain network. Facility location problem (FLP) is a well-established research area within operations research (Melo *et al.*, 2009) which deals with this kind of problems. The simplest versions of the FLP are the p-median problem and the uncapacitated facility location problem (UFLP). The p-median problem consists on a set of customers and a set of potential facilities locations distributed in a space. Each customer has its own demand, and distances or costs between each customer and each potential facility location are known. The objective is to locate N facilities at N locations of the set of potential locations in order to minimize total cost for satisfying the demand of customers. The UFLP is similar to the p-median problem. The only difference is that the number of facilities to be located is not predetermined. In the UFLP, a fixed opening cost is defined per potential facility and thus, the number of facilities located is an output of the model (Reese, 2006). Moreover, the capacity of the facilities is not limited. The p-median and the UFLP problem are characterized by having deterministic parameters, a single product and a single period planning horizon.

In the mathematical formulation of the UFLP proposed by Erlenkotter (1978) there is a set *I* of *m* alternative facility locations, indexed by *i* and there is a set J of *n* customers, indexed by *j*. There are two sets of decision variables X_{ij} and Y_i. Variable X_{ij} represents the fraction of the demand of customer *j* that is satisfied by facility *i* and variable Y_i is a binary variable that takes a value of 1 if facility *i* is opened and 0 otherwise. Concerning costs, f_i is defined as the fixed opening cost of facility i and C_{ij} is defined as the total production and distribution cost of satisfying demand of customer *j* with facility *i*. The resulting MILP is presented below:

$$Min \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}X_{ij} + \sum_{i=1}^{m} f_i Y_i \tag{4.1}$$

Subject to:

$$\sum_{i=1}^{m} X_{ij} = 1 \qquad \forall j \in J \tag{4.2}$$

$$X_{ij} \leq Y_i \qquad \forall i \in I, \forall j \in J \tag{4.3}$$

$$X_{ij} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{4.4}$$

$$Y_i \in \{0,1\} \qquad \forall i \in I \tag{4.5}$$

The objective function (4.1) minimizes total cost including opening costs, production costs and distribution costs. Constraint (4.2) ensures that the demand of each of the customers is satisfied and constraint (4.3) defines the fact that only opened facilities can satisfy customers demand. There exists many variants and extensions of the facility location problem. The main of them are described below:

1. **Capacitated facility location problem (CFLP):** In this extension of the UFLP, the capacity of the facilities is included in the problem. In that way, the allocation and the location decisions are taken based not only in cost and distance but also in the capacity of the facilities to satisfy customers demand. (Wu and Zhang, 2006). As in the UFLP, parameters included are deterministic, and it deals with single period planning horizon problems.

2. **Multi-period facility location problem (MFLP):** This version of the facility location problem is used for cases where the parameters of the problem (*i.e.* demand, capacity, etc.) change over time. The way in which parameters evolve is predictable; hence, time horizon is divided in a finite number of periods and different values are defined for each parameter at each period (Nickel and Saldanha-da-Gama, 2015). Given that parameters such as demand could vary significantly from one period to another in the MFLP, at each period facilities could be closed and relocated. Hence fixed opening, closing and relocating costs are included in the model (Klose and Drexl, 2005).

3. **Multi-product facility location problem:** In models that aggregate demand and flow in a single product, it is assumed that facilities requirements in terms of cost and capacity are the same for all the products. However, in reality it is possible to find cases where facility and network requirements are different for each product. The multi-product facility location problem deals with this kind of cases. The simplest version of this problem is the multi-product uncapacitated facility location problem. Other more complex versions define several types of facilities at the same location based on products or define fixed opening costs in function of the product provided by the facility (Klose and Drexl, 2005).

4. **Multi-level facility location problem (MLFLP):** Facility location problems vary also in function of the number of supply chain layers included in the problem. Locations could be decided on the whole or only on a subset of the layers included (Melo *et al.*, 2009). In the traditional MLFLP, there is a set of customers and a set of potential facilities that should be positioned in k levels. The objective is to determine which facilities must be opened at each level, and how flow will be routed through a defined sequence of facilities to the customers minimizing total costs (Ortiz-Astorquiza *et al.*, 2018). Generally, a function is associated to each level; in other words, there are different types of facilities at each level and they play different roles (production, warehousing, etc.). Furthermore, depending on flow constraints two types of MLFLP can be identified: multi-flow models and single-flow models. In a single flow model, demand at one level could only be served by one level higher facilities. In multi-flow

models, demand at each level could be served by any facility at any upper level (Sahin and Süral, 2007).

5. **Stochastic facility location problem**: In many cases in reality, parameters behavior in the future is uncertain (demand, costs, etc.). Stochastic facility location problems integrate uncertainty in the FLP. To this end, parameters behavior is modeled using probability functions. Snyder (2006) provides a literature review on this kind of problems. The main goal of the stochastic location problem is to define a network structure that performs well in an evolving environment. Hence, objective function could be to minimize the expected costs or to maximize the probability of performing well.

6. **Robust facility location problem:** This kind of problem deals with situations where no information about the probability function of the parameters behavior is known. In these cases, the objective is to optimize the worst-case performance of the problem, for example by minimizing the maximum cost over all the possible scenarios. As well as for the stochastic facility location problem, Snyder (2006) provides a literature review on robust facility location problems.

7. **Facility location problem for green logistics:** Facility location problems can also integrate environmental aspects as GHG constraints and recycling facilities location. Waltho *et al.* (2019) and Eskandarpour *et al.* (2015) provide a literature review on facility location problems integrating the environmental thinking.

As it was shown in Chapter 1, SCND models can integrate facility location decisions as well as other tactical decisions such as transportation mode selection, routing decisions, etc. However, in this section we are interested in models dealing only with location and allocation decisions.

4.1.2. Cross-Dock Location Model without Storage Costs at Cross-Docks

In our thesis, we are interested in evaluating at a strategic level, if it is cost-efficient or not to implement a cross-docking consolidation strategy in a supply chain taking into account total delivery volumes (small in the AH case). In that way, the objective of this model is to support strategic decision-making process concerning transport organization. For this reason, we decide to develop a single period deterministic cross-dock location model.

The supply chain considered in this case is composed by a set of suppliers N, a set of potential cross-docking facilities M and a set of warehouses P. Suppliers must satisfy warehouses demand. They have the option of delivering directly all the warehouses or passing through a cross-docking facility in order to deliver them. A supplier cannot deliver its products using both alternatives due to industrial constraints. Products are transported using PCS, LTL or FTL solutions between suppliers and warehouses and using LTL or PCS solutions between the suppliers and the cross-docking facilities. FTL solutions are used between the cross-docking facilities and the warehouses (consolidation). Volume delivered by each supplier i to a warehouse k (V_{ik}), total cost of delivering a cross-docking facility j from supplier i (C_{ij}) and total cost of delivering products from supplier i to all the warehouses directly (C_{i0}) are known. FTL transportation costs and delivery frequencies between the cross-docking facilities and the warehouses are defined based on the volume delivered by suppliers allocated to the cross-docking facilities and the capacity of the FTL transportation mode. It is assumed that there is no stock at the cross-docking facilities (no storage costs at the cross-docking facilities are included). Hence, it is assumed that delivery frequency between the cross-docking facilities and the warehouses is important enough in order to avoid storage costs at cross-docking facilities. Furthermore, we do not take into account cross-docking facilities capacity in this model. Due to small delivery volumes included in this thesis, we assume that cross-docking facilities are able to deal with all the deliveries. The objective of this model is to locate n' cross-docking facilities between the set of potential cross-docking facilities such that total costs are minimized. The linear program developed is presented below and a schema showing input costs for an example is presented in Figure 4.1.:

Sets

$N = \{1..i..n\}$: The set of suppliers.
$F = \{0..j..m\}$: The set of delivery alternatives for each supplier. For a supplier, 0 represents delivering all the warehouses directly and j represents delivering all the products for all the warehouses through the cross-docking facility j.
$M = \{1..j..m\} \subseteq F$: The set of potential cross-docking facilities.
$P = \{1..k..p\}$: The set of Warehouses.

Parameters

C_{ij} ($j \in \{1..m\}$): Total cost per year of delivering products from supplier *i* using cross-docking facility *j*. This cost includes transportation cost between supplier *i* and cross-docking facility *j* and handling cost at the cross-docking facility *j*.
C_{i0}: Total cost per year of delivering products directly to warehouses from supplier *i*. This cost includes transportation costs.
V_{ik}: Total volume (kg) delivered per year by supplier *i* to warehouse *k*.
t_{jk}: Cost of one FTL shuttle between the cross-docking facility *j* and the warehouse *k*.
K_{jk}: Capacity of the transportation mode used between the cross-docking facility *j* and the warehouse *k*.
n': Number of cross-docking facilities to be located.
f_j ($j \in \{1..m\}$): Fixed opening cost of the cross-docking facility *j*

Decision variables

X_{i0}: Takes a value of 1 if supplier *i* delivers all its products directly to all the warehouses, 0 otherwise.
X_{ij} ($j \in \{1..m\}$): Takes a value of 1 if supplier *i* delivers all its products through the cross-docking facility *j* and 0 otherwise.
Y_j ($j \in \{1..m\}$): Takes a value of 1 if the cross-docking facility *j* is used, 0 otherwise.
q_{jk} ($j \in \{1..m\}$): Volume delivered from the cross-docking facility *j* to the warehouse *k*.
N_{jk} ($j \in \{1..m\}$): Number of FTL shipments between the cross-docking facility *j* and the warehouse *k* (delivery frequency per year). It is equal to q_{jk} divided by K_{jk} rounded up to the nearest integer number.

Model

$$\boldsymbol{Objective\ Function}: Min \sum_{i=1}^{n}\sum_{j=0}^{m} C_{ij}X_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{p} t_{jk}N_{jk} + \sum_{j=1}^{m} f_j Y_j \tag{4.6}$$

Subject to

$$\sum_{j=0}^{m} X_{ij} = 1 \quad \forall i \in N \tag{4.7}$$

$$\sum_{j=1}^{m} Y_j = n' \tag{4.8}$$

$$X_{ij} \leq Y_j \quad \forall i \in N, \forall j \in M \tag{4.9}$$

$$q_{jk} = \sum_{i=1}^{n} X_{ij} V_{ik} \quad \forall j \in M, \forall k \in P \tag{4.10}$$

$$q_{jk} \leq N_{jk}K_{jk} \quad \forall j \in M, \forall k \in P \tag{4.11}$$

$$X_{ij} \in \{0,1\} \quad \forall i \in N, \forall j \in F \tag{4.12}$$

$$Y_j \in \{0,1\} \quad \forall j \in M \tag{4.13}$$

$$q_{jk} \in \mathbb{R}^+ \quad \forall j \in M, \forall k \in P \tag{4.14}$$

$$N_{jk} \in \mathbb{N} \quad \forall j \in M, \forall k \in P \tag{4.15}$$

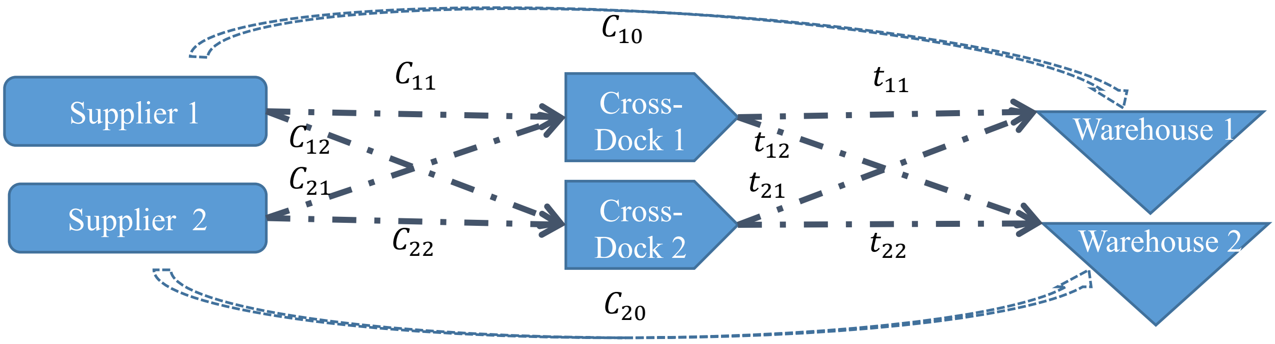

Figure 4.1. Cross-docks supply chain scheme

The objective function (4.6) minimizes the sum between the total cost of delivering products from suppliers to warehouses or cross-docking facilities, the FTL transportation cost between the cross-docking facilities and the warehouses and the fixed opening costs. Constraint (4.7) ensures that for each supplier only one alternative is chosen between delivering products through a cross-docking facility j and delivering all of them directly. Constraint (4.8) defines the number of cross-docking facilities to be located. Constraint (4.9) represents the fact that a cross-docking facility can be used only if it is opened. Constraint (4.10) ensures that products volume that goes from one cross-docking facility j to one warehouse k per year corresponds to the products volume delivered by suppliers using the cross-docking facility j to this warehouse per year. Constraint (4.11) defines the number of FTL shipments per year from cross-docking facility j to warehouse k (N_{jk}) based on total volume delivered and the transportation mode capacity. Finally, constraints (4.12) to (4.15) define variables ranges.

4.1.3. Airbus Case Study

We conduct a case study based on the data file containing deliveries for 2018. In this case, 152 suppliers located in Europe, North America and Morocco and one warehouse located in Albacete are considered. Concerning cross-docking facilities, AH counts with several distribution centres already installed in its supply chain. Currently these distribution centres are not used for inbound transportation. Based on these already existing AH distribution centres we define a set of 6 potential cross-docking facilities. In that way, there are **not fixed opening costs** in this case. Potential cross-docking facilities are located in: London (England), Paris (France), Toulouse (France), Saint Etienne (France), Vitrolles (France) and Zurich (Switzerland). Suppliers and cross-docking facilities locations for Europe are presented in Figure 4.2. Suppliers are in blue (or dark gray), cross-docking facilities are in green (or light gray) and the warehouse at Albacete is in red (or gray).

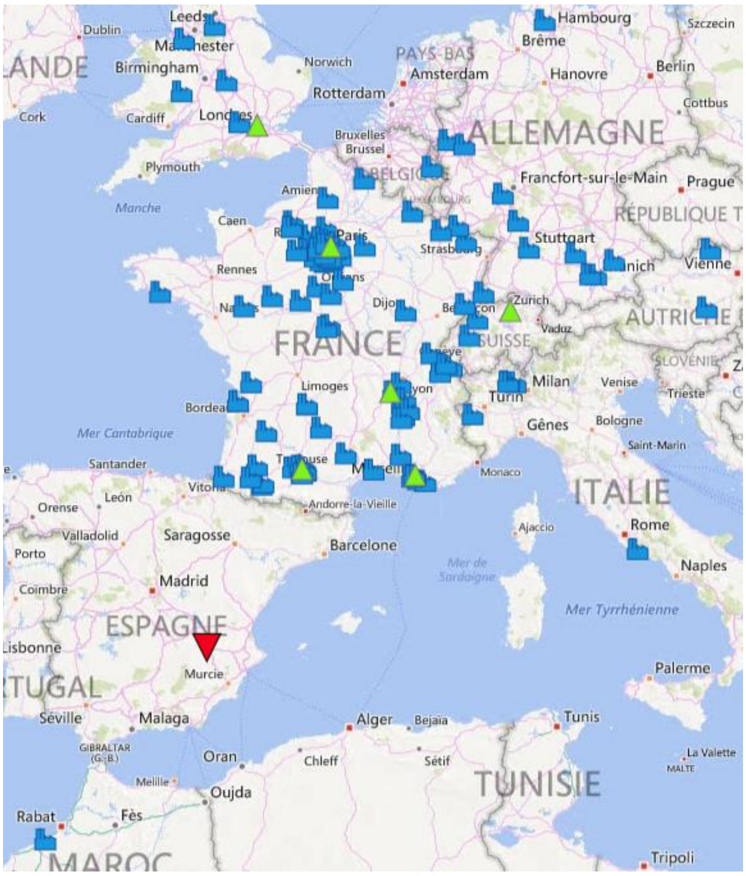

Figure 4.2. Facilities location Europe - Morocco

Total delivery costs between each supplier i and warehouses C_{i0} correspond to transportation costs. Concerning total delivery cost C_{ij} for each couple supplier i – cross-docking facility j, it is calculated as the sum between the transportation cost per year and handling costs per year at the cross-docking facility. Based on information provided by the logistics department we assume that handling cost per pallet is equal to 16€ and that each pallet has a capacity of 1000 kg. Using the database containing shipments for 2018, we estimate total handling costs per year by calculating the number of pallets handled per shipment. In other words, if a supplier delivers a cross-docking facility, there is a transportation cost per year incurred linked to PCS and LTL shipments and a handling cost per year incurred linked to the shipments reception at the cross-docking facilities. The capacity of the FTL transportation mode used between the cross-docking facilities and Albacete is supposed to be equal to 24 tons.

The linear model is run using Supply Chain Guru X, a supply chain design optimizer that uses CPLEX. Results for $n' = 1$ are presented in Table 4.1, Table 4.2 and Figure 4.3. When $n' = 1$ the cross-docking facility at Toulouse is used and total cost is reduced by 25% compared to the current scenario assuming that there is no stock at the cross-docking facility. Transportation cost reduction is due to the consolidation of several PCS and LTL shipments in one FTL shipment. 107 suppliers that deliver 1360 tons per year use the cross-docking facility at Toulouse. For them, mean shipment distance for LTL and PCS delivery methods is reduced from 1123 kilometers to 499 kilometers when they deliver Toulouse instead of delivering directly Albacete. This reduces PCS and LTL shipments cost. FTL supplementary cost from the cross-docking facility to Albacete is smaller than this reduction. Similarly, transportation CO_2 emissions are reduced by 13% due to FTL low emission factors compared to PCS and LTL emissions factors (see Section 2.4.2.). **The FTL emission factor used assumes that the capacity use rate of the truck is bigger or equal to 90%. In this case, 1360 tons are delivered to the cross-dock, which means that the FTL truck used between Toulouse and Albacete makes 57 deliveries with a capacity use rate of 100%.**

Scenario	Croos-docking facities used	Storage Cost per year	Wip Cost Sea Freight	Transport cost per year	Handling costs Cross Docks	Total Cost per year	% Cost Reduction
Current scenario	-	154 K€	99 K€	3,03 M€	0	**3,3 M€**	-
One cross-docking facility	CD_Toulouse	154 K€	99 K€	2,01 M€	213 K€	**2,5 M€**	**-25%**

Table 4.1. Total cost - cross docking facilities location

Scenario	Tons CO2 Emitted per year	% CO2 Reduction
Current scenario	**1277**	-
One cross-docking facility	**1105**	**-13%**

Table 4.2. CO_2 emissions – cross-docking facilities location

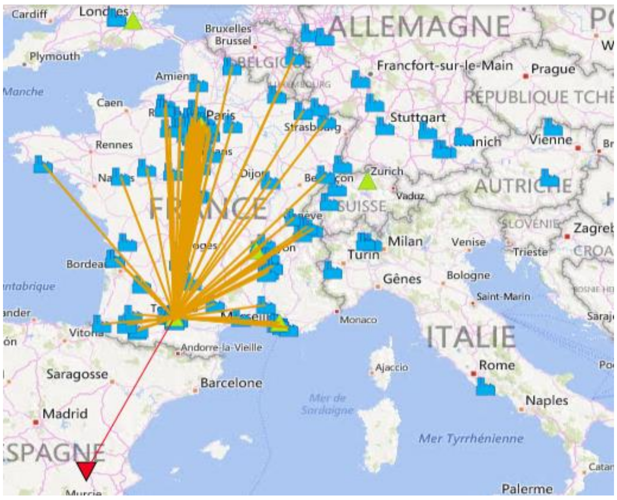

Figure 4.3. Cross-dock location results

As it is mentioned in section 4.1.2., the model used in this case assumes that there is no stock at the cross-docking facilities and does not include storage costs at the cross-docking facilities. It means that it is assumed that the volume delivered to the cross-docking facility is important enough to ensure a high delivery frequency between the cross-docking facility and the warehouse so that the storage cost is negligible. In this case, 1360 tons are delivered to the cross-docking facility at Toulouse. Taking into account that the FTL transportation mode capacity is 24 tons, delivery frequency between Toulouse and the cross-docking facility is 57 times per year (1360 divided by 24 – Table 4.3). With these results, we have estimated storage cost at the cross-docking facility at Toulouse. **Real storage cost in this case is equal to 547 K€** per year. This cost is not negligible. Then, volume delivered to the cross-docking facility in this case study is not enough to avoid storage cost at it.

Volume delivered to the CD at Toulouse (tonnes)	1360
Capacity of the FTL truck (tonnes)	24
Estimated delivery frequency (shipments per year)	57

Table 4.3. Volume delivered to Toulouse Model 1.0

In conclusion, the cross-dock location model without storage costs at cross-docks cannot be used for the AH case. **Storage costs at the cross-docking facilities cannot be avoided** due to small delivery volumes included in this study. For that reason, we will not go further on results analysis. In the next section, we present an improved version of this cross-dock location model that includes storage costs at the cross-docking facilities.

4.1.4. Cross-Dock Location Model with Storage Costs at Cross-Docks

Inventory at the cross-docking facilities depends on the volume delivered to the cross-docking facilities and the delivery frequency between the cross-docking facilities and the warehouses. In this section, we propose a modified version of the first model presented in Section 4.1.2. by fixing the FTL delivery frequency between the cross-docking facilities and the warehouses. We decide to fix this parameter taking into account the fact that input data (shipment sizes, transportation cost, etc.) depend on this parameter. If this frequency is fixed, when a supplier delivers a cross docking facility the total storage cost at it and at the warehouses can be calculated in advance. In that way, input storage costs are pre-calculated for each supplier in function of the delivery choice.

Sets included in the new cross-dock location model with storage costs at cross-docks are the same than in the cross-dock location model without storage costs at cross-docks. Concerning parameters, in this model, total costs C'_{ij} and C'_{i0} include transportation costs and storage costs; storage costs for each supplier vary depending on its delivery choice. If it delivers a cross-docking facility j, storage costs included (at the cross-docking facilities and at warehouses) in C'_{ij} are calculated in function of FTL_{jk}. If it delivers all the warehouses directly, delivery frequency is not modified and the storage cost included in C'_{i0} corresponds to the current storage cost. Similarly, we include the fixed delivery frequencies between cross-docking facilities and warehouses FTL_{jk} and the respective fixed FTL transportation cost t'_{jk}. Variable N_{jk} is removed and a new variable X'_{jk} is included in order to define if a determined cross-docking facility *j* delivers the warehouse *k* or not. New variables and parameters included, and the mathematical model are presented below:

Parameters

C'_{ij} ($j \in \{1..m\}$): Total cost per year of delivering all the products from supplier *i* using cross-docking facility *j* to all the warehouses. This cost includes transportation costs, handling costs and storage cost at the cross docking facilities and at the warehouse in function of FTL_{jk}.
C'_{i0}: Total cost per year of delivering products directly to all the warehouses from supplier *i*. This cost includes transportation cost and storage cost at the warehouses.
FTL_{jk} ($j \in \{1..m\}$): Fixed delivery frequency between the cross-docking facility *j* and the warehouse *k* (Times per year).
t'_{jk} ($j \in \{1..m\}$): Total fixed transportation cost per year of delivering warehouse *k* from the cross-docking facility *j* with a fixed delivery frequency FTL_{jk}.

Decision variables

X'_{jk} ($j \in \{1..m\}$): Takes a value of 1 if the cross-docking facility *j* delivers the warehouse *k*, 0 otherwise.

Model

$$\boldsymbol{Objective\ Function}: Min \sum_{i=1}^{n}\sum_{j=0}^{m} C'_{ij}X_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{p} t'_{jk}X'_{jk} + \sum_{j=1}^{m} f_jY_j \tag{4.16}$$

Subject to

$$\sum_{j=0}^{m} X_{ij} = 1 \quad \forall i \in N \tag{4.7}$$

$$X_{ij} \leq Y_j \quad \forall i \in N, \forall j \in M \tag{4.9}$$

$$q_{jk} = \sum_{i=1}^{n} X_{ij} V_{ik} \quad \forall j \in M, \forall k \in P \tag{4.10}$$

$$q_{jk} \leq X'_{jk} FTL_{jk} K_{jk} \quad \forall j \in M, \forall k \in P \tag{4.17}$$

$$X_{ij} \in \{0,1\} \quad \forall i \in N, \forall j \in F \tag{4.12}$$

$$Y_j \in \{0,1\} \quad \forall j \in M \tag{4.13}$$

$$q_{jk} \in \mathbb{R}^+ \quad \forall j \in M, \forall k \in P \tag{4.14}$$

$$X'_{jk} \in \{0,1\} \quad \forall j \in M, \forall k \in P \tag{4.18}$$

The first part and the last part of the objective function (4.16) are maintained and the second part is replaced by the sum of fixed transportation costs between the cross-docking facilities used and the warehouses. Constraints (4.7), (4.9), (4.10), (4.12), (4.13) and (4.14) are maintained. Constraint (4.8) is removed in this model because the number of cross-docking facilities to be located is limited by the fixed FTL delivery costs between the cross-docking facilities and Albacete. Constraint (4.17) ensures that the quantity delivered from cross-docking facilities to warehouses respect the transportation mode capacity. Finally, constraint (4.18) defines variable range for X'_{jk}.

4.1.5. Airbus case study

We run the model presented previously using Supply Chain Guru X in the same instance based on shipments for 2018 presented in the section 4.1.3. In this case, delivery frequency is fixed between the cross-docking facilities and Albacete. We run the model for several values of FTL_{jk}: twice per month, once per week, twice per week and three times per week. Concerning the input storage cost at the cross-docking facilities, in order to estimate it, in the file containing deliveries for 2018, we define different departure dates from the cross-docking facilities to Albacete for a scenario with a frequency FTL_{jk} equals to 48 times per year (it is assumed that a truck run once every Monday between the cross-docking facility j and the warehouse k). In this way, we estimate the number of days that the parts are kept at the cross-docking facility and then the storage cost. We use the results obtained in this scenario in order to estimate storage cost at the cross-docking facilities for the rest of scenarios *i.e.* storage costs in the scenario where FTL_{jk} is equal to 96 times per year are equal to storage costs obtained for FTL_{jk} equals to 48 dived by two. It is assumed in all the cases that the truck is able to leave with all the products available on stock. In other words it is assumed that workload is smoothed at the cross-docking facilities. Concerning the input storage cost at Albacete, as it is mentioned in chapter 2, it is assumed that mean stock level is equal to mean shipment sizes divided by two. When a supplier delivers a cross-docking facility, the shipment size delivered to Albacete is defined in function of the fixed delivery frequency between the cross-docking facility and Albacete. These storage costs as well as the transportation costs and handling costs are included in the input parameters C'_{ij} and C'_{i0}.

In all the scenarios evaluated with different values for FTL_{jk}, only the cross-docking facility at Toulouse is used because of important fixed delivery costs between the cross-docking facilities and Albacete and small delivery volume per year. In other words, volume delivered by suppliers (1750 tons per year, which is the equivalent of 75 FTL trucks of 24 tons) is not enough to yield a profit by using more than one cross-docking facility. In fact, using an additional cross-docking facility implies that a FTL truck should run FTL_{jk} times per year and with the volume delivered the capacity use rate of the FTL truck used in an additional cross-docking facility would be very low. The minimum cost is obtained for FTL_{jk} equal to 96 times per year/ twice per week. Results are presented in Table 4.4 and Figure 4.4.

Fixed felivery frequecy between CD Toulouse and Albacete	Total Cost
Twice per month - 24 times per year	3,01 M€
Once per week - 48 times per year	2,82 M€
Twice per week - 96 times per year	2,74 M€
Three times per week - 144 times per year	2,8 M€

Table 4.4. Total cost results for different values of FTL_{jk}

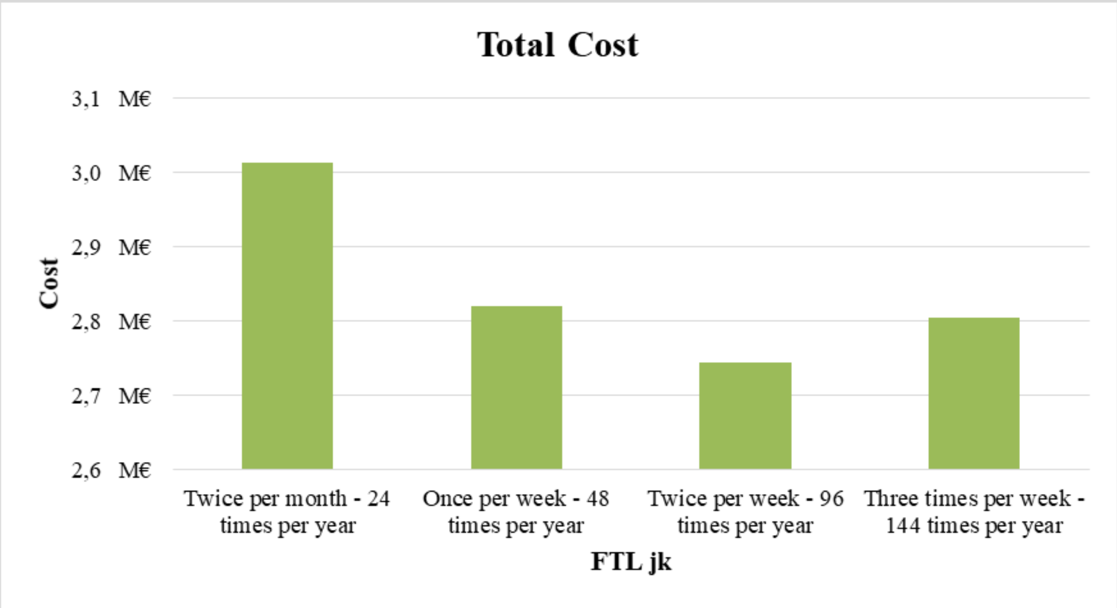

Figure 4.4. Total cost results for different values of FTL_{jk}

Detailed resulting total costs for FTL_{jk} equals to 96 times per year (the minimum cost fixed delivery frequency) compared to the current scenario are presented in Table 4.5. By using the cross-docking facility at Toulouse and fixing a delivery frequency of 96 times per year between Toulouse and Albacete, total cost per year could be potentially reduced by 16% from 3,3 M€ to 2,7M€. Cost reduction is due the consolidation of several PCS and LTL shipments in one FTL shipments. In this case, 107 suppliers over 152 suppliers deliver the cross-docking facility at Toulouse. For these suppliers mean LTL and PCS shipment distance is reduced from 1256 kilometers to 522 kilometers by delivering Toulouse instead of delivering Albacete and PCS and LTL transportation cost reduction achieved delivering the cross-docking facility is bigger than supplementary handling cost, storage cost and FTL transportation cost from Toulouse to Albacete.

Scenario	Cross-docking facities used	Storage Cost per year	Wip Cost Sea Freight	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	% Cost Reduction
Current scenario	-	154 K€	99 K€	3,03 M€	0	**3,3 M€**	-
Cross-docking facilities location scenario	CD_Toulouse	281 K€	99 K€	2,15 M€	212 K€	**2,7 M€**	**-16%**

Table 4.5. Total cost current scenario vs cross-dock location scenario -FTL_{jk} = 96

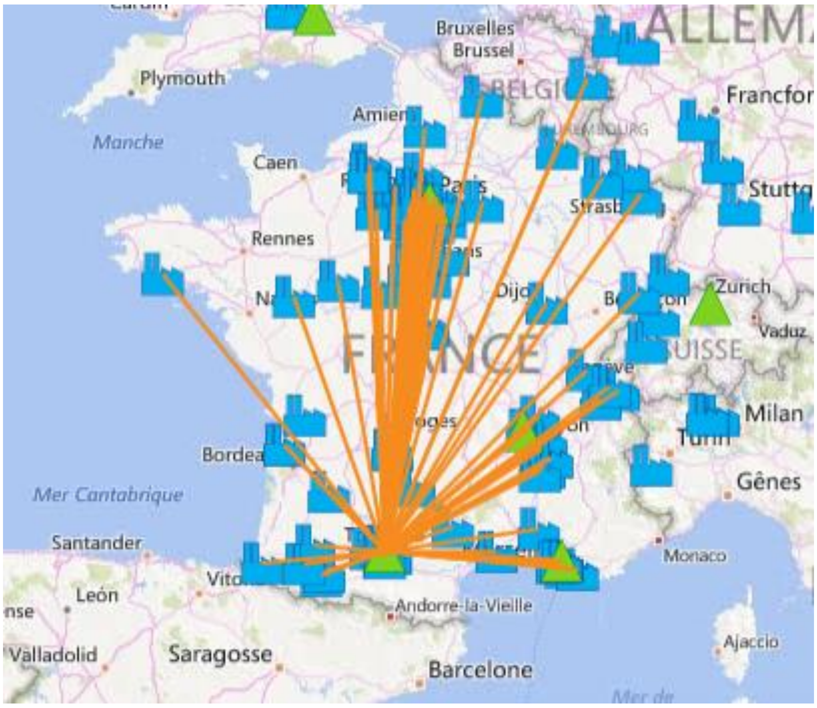

Figure 4.5. Suppliers allocation model 2.0

Volume delivered to the cross-docking facility is equal to 1587 tons per year (64% of the total volume). Taking into account the fact that delivery frequency between Toulouse and Albacete is 96 times per year, mean FTL shipment weight is equal to 17 tons, and hence the estimated capacity use rate is equal to 69% (FTL transportation capacity is equal to 24 tons).

Volume delivered to the CD at Toulouse (tons per year)	1587
Capacity of the FTL truck (tons)	24
Mean capacity use rate	69%

Table 4.6. Volume delivered to Toulouse Model 2.0

Concerning CO_2 emissions, in this case we estimate transportation emissions and cross-docking emissions. Regarding FTL transportation between Toulouse and Albacete, given that mean capacity use rate of the FTL truck used between Toulouse and Albacete is less than 90%, we cannot use the emission factor presented in Section 2.4.2. In this case, we use a FTL emission factor of 94 g of CO_2/ton km, which corresponds to the emission factor of a FTL road transportation mode with a capacity use rate of 69% (McKinnon and Piecyk, 2011). In order to estimate the cross-docking CO_2 emissions, we assume that the mean area occupied by products delivered to the cross-docking facility (including loading, unloading and circulation area) is equal to 138.72 m². We make this assumption based on the fact that one truck run twice per week between Toulouse and Albacete, hence the surface occupied in the cross-docking can be approximated to the base of a semi-trailer which is 13.6 m x 2.55 m multiplied by 4 (in order to include loading, unloading and circulation areas). For a traditional warehouse in France, mean energy consumption is equal to 130 kWh per meter per year (ENEA Consulting and CETIAT, 2014) and in average, 0.0571 Kg of CO_2 are produced per kWh (Bilans GES ADEME, 2019b). Hence, for 138.72 m², 1 ton of CO_2 is produced per year. Transportation and cross-docking CO_2 emissions are presented below in Table 4.7 for the current and the cross-dock location scenario.

Source	Current Emissions (Tons per year)	Cross-dock location scenario emissions (Tons per year)
Air transportation	580	580
Road transportation	688	524
Sea transportation	10	10
Cross-docking	0	1,0
Total	**1277**	**1115**

Table 4.7. Current CO_2 emissions vs cross-dock location CO_2 scenario emissions

By using the cross-docking facility at Toulouse, total CO_2 emissions are reduced by 13%. As for model 1.0 transportation CO_2 emissions reduction is due to mean LTL and PCS shipment distance reduction (suppliers deliver Toulouse instead of delivering directly Albacete) and the low FTL emission factor for transportation between Toulouse and Albacete. Cross-docking CO_2 emissions are negligible compared to transportation CO_2 emissions.

Finally, in this case, stock is managed at the cross-docking facilities due to the difference between delivery frequencies to the cross-docking facility and the fixed delivery frequency between the cross-docking facility and Albacete. In chapter 5, we will combine cross-docking location with transportation lot sizing in order to avoid completely stock at the cross-docking facilities.

4.1.6. Conclusion

Cross-dock location is a logistics strategy that allows consolidating LTL and PCS shipments in order to reduce transportation costs and improve transportation capacity usage. In this section, we study a supply chain composed by a set of suppliers, a set of potential cross-docking facilities and a set of warehouses. Suppliers have the option of delivering warehouses directly or through a cross-docking facility. The objective is to locate a set of cross-docking facilities that minimize total logistics costs. To this end, we propose two cross-dock location models: a cross-dock location model without storage costs at cross-docks and a cross-dock location model with storage cost at cross-docks.

The first model assumes that delivery frequency between cross-docking facilities and warehouses is important enough to avoid storage at cross-docks. We test this model in the AH instance containing deliveries for 2018. Based on results, it is shown that storage costs at the cross-docking facilities need to be included.

For this reason, we propose the second model. This model fixes the delivery frequency between the cross-docking facilities and the warehouses. In that way, input storage costs are pre-calculated for each supplier in function of the delivery choice.

We run the cross-dock location model with storage costs at cross-docks for several values of the fixed delivery frequency between the cross-docking facilities and Albacete. The minimum total cost is obtained when it is equal to 96 times per year (twice per week). In all the cases, only the cross-docking facility at Toulouse is used due to small delivery volumes included in this study. As a result, by using the cross-docking facility at Toulouse and fixing the delivery frequency between Toulouse and Albacete to twice per week, total cost and CO_2 emissions could be potentially reduced by 16% and 13% respectively (under the condition that workload is smoothed at the cross-docking facility at Toulouse). This is due to PCS and LTL shipments consolidation in FTL shipments.

Finally, as it is mentioned at the beginning of this chapter, at AH, implementing consolidation strategies requires modifying the current transportation organization in which 80% of suppliers manage transportation and there is no visibility over transport operations. Taking into account the results obtained, it is recommendable for AH to modify the current transportation organization in order to have control over all the inbound flows and be able to implement consolidation strategies such as cross-dock location. Companies in the aeronautic industry with similar characteristics (See Table 2.16 in Chapter 2) can consider implementing a cross-docking strategy in function of delivery volume and suppliers' location. Delivery volume to the cross-docking facilities must be enough to achieve an acceptable level for the transportation mode capacity use rate between the cross-docking facilities and the final destination. In our case 1587 tons are delivered to the cross-docking facility per year and there are 96 FTL shipments per year between the cross-docking facility and Albacete. This allows achieving a capacity use rate of 69% for the FTL transportation mode.

Cross-dock location will be studied in chapter 5 in conjunction with transportation lot sizing and transportation mode selection axes. In chapter 6, we will integrate the environmental thinking in our cross-dock location model.

4.2. Milk Run Concept

As cross-dock location, the milk run concept is a solution that allows consolidating several LTL and PCS shipments in one FTL shipment. In this section, we study the possibility of implementing milk runs that allow consolidating shipments for a cluster of suppliers around the cross-docking facilities. To this end, firstly, we conduct a literature review on the milk run concept. Afterwards we propose a model that allows estimating the milk run cost and comparing it with direct delivery transportation concepts for a cluster of suppliers. Finally, we present a case study for the suppliers of AH located in the Parisian region in order to illustrate an application of the model developed. We select the Parisian region, because it is the region with the highest density of suppliers (approximately one supplier every 23 km), which makes the implementation of the milk run strategy there appropriate.

4.2.1. Literature Review

Milk Run is a transportation concept defined by Baudin (2004) as "pickups and deliveries at fixed times along fixed routes". Milk Runs can be applied to inbound logistics or outbound logistics. Within this thesis, we focus on the inbound case. Brar and Saini (2011) define milk-run logistics in the inbound case as a procurement method in which a truck is dispatched from a central depot at a specified time to visit various suppliers following a predefined route to collect parts or products and deliver them to the central depot (see Figure 4.6). Main advantages of milk-run logistics are:

1. **Transportation costs reduction:** The fact of consolidating several LTL shipments in one FTL shipment allows reducing transportation costs.

2. **Reliability and storage costs reduction:** Milk runs allow having a major level of reliability because of synchronization. It is considered as a lean procurement method, which allows increasing delivery frequencies and reducing inventory costs. For example, it is possible to replace three FTL shipments coming from three different suppliers to a depot, taking place at the beginning of the week, with three milk runs

taking place three times per week and visiting the three suppliers to after deliver the depot. The milk runs will deliver three times per week a LTL shipment per supplier that is equal to the FTL shipment divided by 3. This reduce picking quantities, storage costs, and improves reliability without increasing significantly transportation cost.

3. **Vehicle loading rate improvement:** By consolidating several LTL shipments in one FTL shipment vehicle-loading rate could be improved if the sum of the LTL shipments weights is enough to fit vehicle's capacity.

4. **Transportation distance reduction and CO_2 reduction:** In cases where milk runs are implemented in order to consolidate several LTL direct shipments in one FTL shipment without increasing delivery frequency from suppliers to the final destination, transportation distance is reduced and thus, CO_2 emissions are reduced too.

Meyer (2015) propose a list of attributes in order to characterize the milk run concept in function of planning and physical transportation:

1. **Tour planning:** Milk run planning operations could be conducted by the consignee or by a logistics service provider.

2. **Degree of Consolidation:** Tours could be exclusively dedicated to the consignee shipments (dedicated tours) or could include third party shipments. In the second case, the logistics services provider in charge of the milk run includes third party shipments in order to improve transportation capacity use rate.

3. **Direct or indirect service:** Milk runs could deliver or not a consolidation or a transhipment facility before delivering the final destination.

4. **Regularity:** Milk runs could be modified on a daily basis depending on demand, or they could be planned and fixed for a defined time horizon using regular transportation plans. Regular tours may be cheaper than irregular tours.

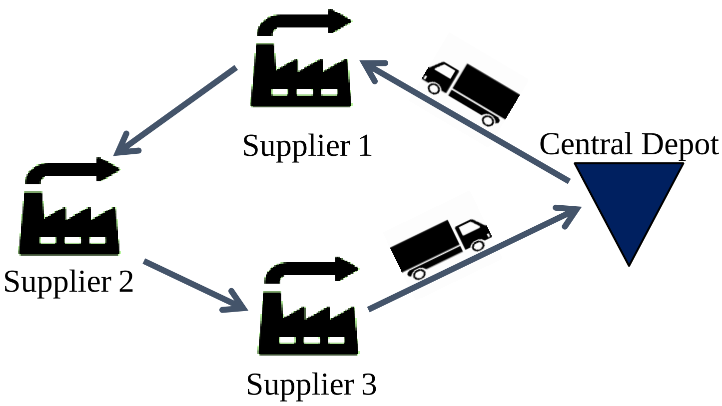

Figure 4.6. Milk Run Example

In the AH case, we are interested in evaluating the implementation of milk runs for a cluster of suppliers from an economic point of view. Hence, we are interested in literature dealing with milk run cost estimation and comparing milk run concept with LTL and parcel and courier services (PCS) transportation concepts. Routing models are out of the scope of this section.

Generally, milk runs are conducted by logistics services providers. However, a buyer must be able to evaluate milk run costs and compare them with other transportation concepts. A commonly used approach when estimating milk run cost is the activity based costing method. This method “estimates the cost of all the relevant activities of the transportation concept based on statistical data for a region or country” (Meyer, 2015). Relevant activities costs concern staff costs, diesel costs, fixed vehicle costs, variable vehicle costs, etc. The cost obtained may be increased in order to take into account logistics providers profit margin. Other approach is proposed by Senoussi *et al.* (2018). They develop a production-inventory-distribution problem. In their model, there is a production facility that must supply a set of retailers concentrated in a region far away from the production facility. The objective is to determine the setup periods and quantities to be produced, retailers to be visited and quantities to be delivered each period and vehicles to use and the retailers to be visited by each vehicle each period. No routing decisions are included. In their model, it is assumed that there is a fixed transportation cost incurred each time that a vehicle travel from the production facility to the cluster of retailers and a fixed service cost each time a vehicle visits a new retailer inside the cluster. The distance between the retailers is negligible compared to the distance between the production facility and the cluster of retailers. Hence, fixed transportation cost to the cluster from the production facility is determined based on distance and service costs inside the cluster depend only on material handling cost at each stop.

Finally, regarding the milk run transportation concept evaluation compared to other transportation concepts, the simplest approach when assigning transportation concepts to suppliers is the weight-based allocation method. This method defines two weight limits W_{min} and W_{max}. For suppliers whose shipment weight is less than W_{min}, PCS method is used, for customers whose shipment weight is bigger than W_{max} a FTL method is assigned and for the rest of the suppliers a milk run is used (Meyer, 2015). Branke *et al.* (2007) propose a model that allows comparing PCS, FTL, hub delivery and milk run transportation concepts. They use an evolutionary algorithm in order to assign shipments to each transportation concept in parallel with an evolutionary algorithm to optimize routes within each channel. Meyer and Amberg (2018) develop a mathematical model that allows assigning transportation concepts: FTL, PCS or milk run, to suppliers in function of transportation and storage costs. Optimal delivery frequencies are estimated for FTL and PCS methods. Concerning milk runs, they propose an algorithm that allows generating feasible milk runs for each type of vehicle taking into account capacity and driving time constraints. Routing costs are estimated for each feasible milk run. In parallel, different delivery patterns are defined per supplier. They allow estimating storage costs for the milk run concept. Models comparing milk run and other transportation concepts found in literature require generating feasible tours. However, due to the strategic nature of our case, designing tours is out of the scope of this thesis. In the next section, we provide a strategic approach in order to evaluate the milk run concept without using tour generation.

4.2.2. Milk Run Evaluation Model

We develop a milk run evaluation model in order to define if it is profitable or not to implement the milk run concept around a cross-docking facility. As it was mentioned before, to the best of our knowledge, models found in literature concerning milk run evaluation include routing. In our case, due to the strategic nature of our problem, routing is out of the scope. We propose a simpler approach in order to estimate the cost of the implementation of a milk run concept for a cluster of suppliers and compare it with other concepts. We assume that routing is optimized. We divide our milk run evaluation approach in two parts. The first part defines an activity based costing method (Meyer, 2015) in order to estimate mean transportation cost for a milk run and the second part proposes a framework that allows evaluating milk run implementation for a cluster of suppliers around a cross-docking facility using the mean milk run cost estimated in the first part.

4.2.2.1. Mean milk run cost estimation

In order to estimate mean transportation cost for a milk run we propose an activity-based costing method using data provided by the Comité National Routier (Comité National Routier, 2020). In Table 4.8 we can see the main operation costs associated with the operation of a vehicle having a payload between 3.5 tons and 19 tons.

Item	**Cost**
Fuel / km	0,241 €/km
Pneumatics / km	0,024 €/km
Maintenance and repair / km	0,1 €/km
Kilometre term	**0,365 €/km**
Wages / hour	14,96 €/h
Wages charges / hour	2,78 €/h
Hourly term	**17,74 €/h**
Vehicle carrying cost / day	56,45 €/day
Insurance / day	10,28 €/day
Taxes / day	0,56 €/day
Structure charges and other indirect charges / day	124,27 €/day
Total cost per day	**191,56 €/day**

Table 4.8. Operation costs- semitrailer (Comité National Routier, 2020)

In our model, we assume that milk runs take place during one working day. The average speed in the Parisian ring road is 38.9 km/h (Paris, 2019). We assume that this is the average speed for milk runs. Additionally, according to the CNR, mean service time per day for a freight vehicle is 9.5 hours and driving time is 60% of the service time. Hence, for a speed of 38.9 km/h mean distance traveled per day is equal to 222 km. Assuming that the distance traveled during a milk run correspond to the distance estimated, that it takes 9.5 hours and using the costs presented in Table 4.7, the estimated milk run cost for an average speed of 38.9 km/h is **441€**. Kilometric, hourly and daily costs repartition is presented in Figures 4.7.

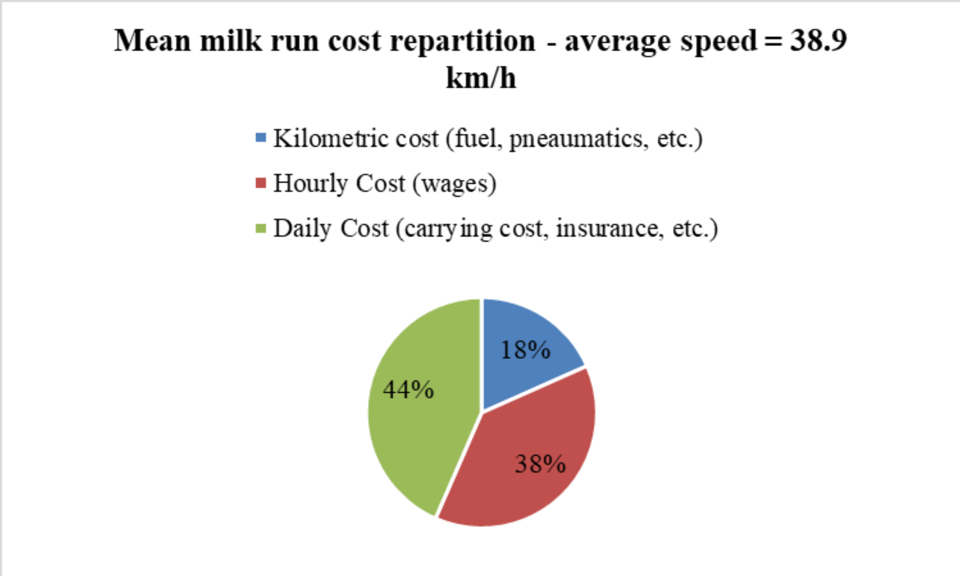

Figure 4.7. Costs repartition average speed = 38.9km/h

If it is assumed that milk runs are conducted by a logistics services provider, it is necessary to add profit margin to the cost estimated. This profit margin may vary between 20 and 40% (Audrex, 2017).

4.2.2.2. Milk run evaluation

We are interested in evaluating the implementation of milk runs for a cluster of suppliers around a cross-docking facility at a strategic level. In other words in our problem there is a set of vehicles that leave from the cross-docking facility in order to visit the suppliers in the cluster, pick their shipments and after return to the cross-docking facility. To this end, we propose estimating milk run cost for two scenarios:

1. In the first scenario, we assume that the logistics services provider includes third party shipments in order to improve transportation capacity use rate. For this scenario, we assume that the logistics services provider is able to include third party shipments in a way that the transportation capacity is fully (100%) used. Thus, the milk run cost for a shipment is estimated using the mean milk run cost estimated previously on a prorated basis of the shipment weight divided by the transportation mode capacity. In other words, in this scenario, the cost of delivering a shipment using the milk run concept is equal to the shipment weight divided by the capacity of the transportation mode used for the milk run, multiplied by the mean milk run cost estimated. This cost can be after compared to PCS and LTL costs. This is a very optimistic scenario.

2. In the second scenario, we assume that milk runs do not include third party shipments. Only the shipments provided by the suppliers in the cluster are included. To this end, let us assume that V is the total volume delivered per year for the suppliers included in the cluster, H is the number of suppliers in the cluster and F is a fixed delivery frequency per year for the suppliers included in the cluster. If we assume that L is the number of suppliers visited per milk run then it is necessary to do $\left\lceil \frac{H}{L} \right\rceil$ milk runs in order to visit all the suppliers in the cluster. Let us call this value Z. If, MR is the estimated milk run cost and K is the capacity of the transportation mode used for the milk run, then the total

transportation milk run cost per year for the suppliers in the cluster (*MR cost per year*) is :

$$MR\ cost\ per\ year\ =\ F * Z * MR \qquad (4.19)$$

Subject to:

$$F * Z * K \geq V \qquad (4.20)$$

Storage costs and handling costs for suppliers included in the milk runs must be estimated in function of F. The resulting total cost for this milk run scenario is the sum between total storage cost and total transportation cost. Additionally, F must be defined in a way that the milk run capacity is enough to pick up all the volume delivered by the suppliers included in the milk run per year (4.20). This cost can be after compared with the PCS an LTL cost.

Both of the approaches defined before allow evaluating the profitability of implementing the milk run concept for a cluster of suppliers. We propose these approaches because of the strategic nature of this thesis. Routing is out of the scope of this study. Even if the results of the application of this model suggest that the implementation of the milk run may be profitable, the decision maker should go further on his/her analysis by evaluating the planning effort required for implementing the milk run strategy.

4.2.3. Airbus Case Study

In order to show an application of the model defined before, we conduct a case study for a cluster of suppliers located around the cross-docking facility at Paris using the data file containing shipments for 2018. To this end, we select suppliers located in a radius of 80 kilometers around the cross-docking facility (Figure 4.8), in total there are 38 suppliers in this perimeter and they deliver 421 tons per year. In average there is one supplier every 23 km**.**

Figure 4.8. Suppliers inside a radius of 80 km of the Paris cross-docking facility

As this optimization axis needs to be studied in conjunction with the cross-dock location axis, no conclusion about the profitability of the milk run concept for AH can be inferred in this Section. Cross-dock location will be studied in conjunction with the milk run

concept in Chapter 5. Moreover, we select the cross-docking facility at Paris in order to illustrate an application of the model presented in the previous section as there is an important concentration of suppliers in the Parisian region.

Concerning the milk run cost, we assume that profit margin for the logistics provider is 40%. Hence, for an average speed of 38.9 km/h mean milk run cost is equal to 735 € based on the mean milk run cost estimated in the previous section. Similarly, we assume that the capacity of the truck used in the milk run is equal to 13 tons. Taking into account these assumptions, we evaluate the direct delivery scenario and the two milk run scenarios presented in Section 4.2.2:

- **Direct delivery scenario:** Using the data file containing deliveries for 2018, we retrieve shipments for the 38 suppliers inside the perimeter of the cross-docking facility at Paris. Based on shipment weights we estimate direct delivery LTL and PCS transportation costs from suppliers to Paris using UPS and DHL tariffs. In this scenario, shipment sizes are not modified.

- **Milk run scenario 1:** In this scenario, we implement the milk run concept including third party shipments for suppliers in the Paris cluster. Shipment sizes are not modified.

- **Milk run scenario 2:** Here, we implement the milk run concept without including third party shipments. It is assumed that milk runs take place once per week (F = 48 times per year). For an average speed of 38.9 km/h it is assumed that the number of suppliers visited per milk run (L) is equal to 7.

Total transportation cost, handling cost, and storage cost are estimated for each one of the scenarios defined before. Results are presented in Table 4.9.

Average Speed = 38.9 km/h			
Cost	**Direct Delivery**	**Milk Run Scenario 1**	**Milk Run Scenario 2**
Transportation Cost	165 K€	24 K€	212 K€
Handling Cost	71 K€	71 K€	34 K€
Storage Cost	43 K€	43 K€	115 K€
Total Cost	**279 K€**	**137 K€**	**361 K€**

Table 4.9. Milk run evaluation results

The first column in Table 4.9 show costs for the scenario in which suppliers deliver directly the cross-docking facility at Paris using LTL or PCS solutions. The second column show costs for the milk run scenario 1 and the third column shows costs for the milk run scenario 2. In the direct delivery scenario and the milk run scenario 1, shipment sizes are not modified hence storage costs and handling costs are the same. In the third scenario, shipment sizes are modified in function of F and storage costs and handling costs change. With the implementation of the milk run concept including third party shipments, total cost could be potentially reduced by 51% compared to direct delivery scenario. In the other hand, implementing the milk run concept with a delivery frequency of once per week including only the AH shipments is not profitable for the company, it increases cost by 29% compared to the direct delivery scenario. This is due to small delivery volumes and delivery frequency reduction. In the milk run scenario 2, when implementing the milk run strategy with a delivery frequency of once per week for suppliers in the Paris cluster, delivery frequency is reduced for 82% of the suppliers compared to the direct delivery scenario, which increases storage costs.

In fact, mainly three factors influence the profitability of a milk run strategy in the milk run scenario 2:

1. **Volume delivered:** Volume delivered should be important enough in order to use the milk run capacity.

2. **Delivery frequency and storage cost:** When implementing the milk run strategy in the milk run scenario 2, delivery frequency for the suppliers included in the milk run is modified. Hence, for example if delivery frequency is reduced for a supplier that provides expensive parts, storage costs may increase significantly. Similarly, delivery frequency defined can increase or decrease handling costs.

3. **Number of suppliers visited per milk run:** The greater is the number of suppliers visited per milk run, the smaller the milk run scenario 2 cost.

As an example, if we remove one of the suppliers of the milk run (SAGEM) providing expensive parts, we multiply volume delivered by suppliers by 2 (827 tons per year) and we increase the number of suppliers visited per milk run to 10, the milk run scenario 2 becomes cheaper than the direct delivery scenario (results are shown in Table 4.10).

Cost	**Direct Delivery**	**Milk Run Scenario 2**
Transportation Cost	209 K€	155 K€
Handling Cost	72 K€	38 K€
Storage Cost	65 K€	140 K€
Total Cost	**347 K€**	**333 K€**

Table 4.10. Results without SAGEM, with volume delivered multiplied by 2 and L=10

In fact, the milk run scenario 2 is very sensitive to the three factors presented previously. The objective of the case study presented in this section is to illustrate an application of the milk-run evaluation model. The conclusions obtained do not allow drawing an overall conclusion of the profitability of the milk run concept for AH. It is necessary to study the milk run concept in conjunction with the cross-dock location optimization axis in order to be able define if the milk run strategy could be appropriate or not for the AH case. This will be addressed in chapter 5.

4.2.4. Conclusion

In this section, we propose a model in order to evaluate the implementation of a milk run strategy for a cluster of suppliers around a cross-docking facility. To this end, we develop an activity based costing method in conjunction with a framework in order to evaluate potential benefits of its implementation. We conduct a case study for suppliers located in a radius of 80 kilometers around the cross-docking facility in Paris. As a result it is shown that compared to a direct delivery strategy, the milk run strategy including third party shipments could potentially reduce total cost by 51%. Conversely, implementing a milk run strategy including only the Airbus shipments with a delivery frequency of once per week and 7 suppliers per milk run would not be profitable for the company due to small delivery volumes and delivery frequency reduction. Results obtained with this case study do not allow drawing an overall conclusion of the potential benefits of the milk run strategy for AH and the aeronautic industry. It is necessary to study this strategy in conjunction with cross-dock location. In the next chapter, we will combine all the optimization axes addressed in chapters 3 and 4 in order to build an optimized transport solution for AH from an economic point of view.

5. How to Build an Optimized Inbound Supply Chain Network

In this chapter, we will combine all the optimization axes studied in the previous chapters in order to build an optimized inbound supply chain network for AH gradually. This solution is developed under the lean supply chain paradigm. Hence, we will focus mainly on costs reduction. Moreover, we will use the same AH instance based on 2018 deliveries. This database fits the AH current situation given that transport management has not been modified and volumes stay in the same order of magnitude. The step-by-step approach used for building the optimized inbound supply chain network as well as the optimization axes used, can be considered in industries similar to the AH industry (see characteristics defined in Table 2.16 in Chapter 2). Table 5.1 present a summary of all the scenarios that will be evaluated in this chapter.

Scenario	Description
Orders grouping + Sea for all North American suppliers scenario	Transportation lot sizes are optimized including sea freight as a transportation mode alternative for all the North American suppliers
Optimized scenario 1	Transportation lot sizing, sea freight inclusion and cross-dock location are combined. A new cross docking facility located at New York is included. A FTL sea freight solution (the full capacity of a container is used) is used between New York and Albacete
Optimized scenario 2	Transportation lot sizing, sea freight inclusion and cross-dock location are combined. A LTL sea freight solution (only a part of the capacity of a container is used) is used between New York and Albacete.
Optimized scenario 3	Transportation lot sizing, sea freight inclusion and cross-dock location are combined. A LTL sea freight solution (only a part of the capacity of a container is used) is used between New York and Albacete. We force the cross-dock location model to use the cross-docking facilities at Paris and New York
Milk run scenario 1	This scenario evaluates the implementation of the milk run concept including third party shipments for the optimized scenario 2 around the cross-docking facility at Toulouse.
Milk run scenario 2	This scenario evaluates the implementation of the milk run concept including only the AH shipments for the optimized scenario 2 around the cross-docking facility at Toulouse.
Milk run scenario 3	This scenario evaluates the implementation of the milk run concept including third party shipments for the optimized scenario 3 around the cross-docking facility at Paris.
Milk run scenario 4	This scenario evaluates the implementation of the milk run concept including only the AH shipments for the optimized scenario 3 around the cross-docking facility at Paris.

Table 5.1. Scenarios summary

5.1. Transportation lot sizing and Transportation mode selection

As it is shown in chapter 2, currently at AH, transportation lot sizes for suppliers are optimized only in function of storage costs, resulting in small shipment sizes and big delivery frequencies. In chapter 3, we show that by optimizing transportation lot sizes in function of storage costs and transportation costs, total cost and CO_2 emissions could be reduced by 40% and 24% respectively (see Section 3.1.3). On the other hand, suppliers included in this study use mainly three transportation modes to deliver AH: airfreight, sea freight and road freight. Shipments coming from Europe are delivered using road freight, shipments coming from United States and Canada are delivered using airfreight and shipments coming from Morocco are delivered using sea freight. Concerning Mexico, shipments going to Marignane are delivered using airfreight and shipments going to Donauworth are 80% delivered using Sea freight and 20% delivered using airfreight. In chapter 3, we show that by including sea freight in transportation mode alternatives for all the suppliers located in North America total cost could be reduced by 2% and CO_2 emissions are reduced by 22% (see Section 3.2.3).

In this section, we combine transportation lot sizing with transport mode selection for the Airbus case. To this end, we use the transportation lot sizing model proposed in section 3.1, and we include the sea freight LTL and FTL delivery methods as alternatives for all the suppliers located in North America (in section 3.1.3. transportation lot sizes were estimated taking into account only current transportation modes). In other words, in the transportation lot sizing model, we select the cheapest alternative for North American suppliers, between airfreight and sea freight. We maintain the same hypothesis defined in chapter 3: 1) suppliers using sea freight in North America must deliver the port at New York using road freight 2) the arrival port is located in Valencia and parts need to be transported using road freight from the port of Valencia to Albacete and 3) sea freight delay is equal to 18 days.

Results are presented below in Table 5.2 and Figure 5.1. By optimizing transportation lot sizes and including sea freight as an alternative for all the suppliers located in North America (not only for Mexico) total cost is reduced by 41% compared to the current scenario, from 3,3 M€ to 1,95 M€. Cost reduction is mainly due to transportation lot sizes optimization: as in section 3.1, delivery frequency is reduced for 99% of the suppliers. By including sea freight as an alternative for all the North America shipments, only 1% supplementary cost reduction is achieved in comparison to the scenario where transportation lot sizes are optimized maintaining current transportation mode constraints (sea freight is included only for Airbus Mexico; see section 3.1.3).

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Total Cost per year	% Cost Reduction
Current scenario	154 K€	99 K€	3,03 M€	3,3 M€	-
Orders grouping + Sea for all North American suppliers scenario	599 K€	124 K€	1,22 M€	1,95 M€	**-41%**

Table 5.2. Transportation lot sizing + sea freight as an alternative for all cost

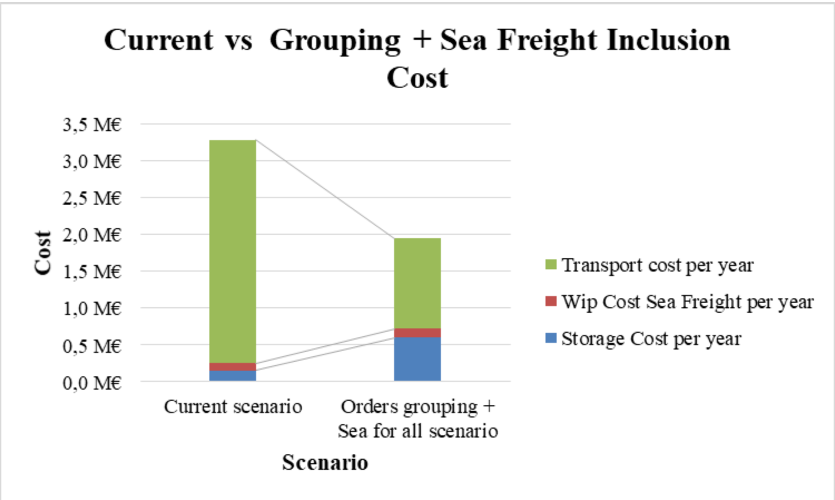

Figure 5.1. Transportation lot sizing + sea freight inclusion as an alternative for all North America suppliers cost

In fact, when sea freight is included as an alternative for all the suppliers located in North America in the transportation lot sizing optimization, two additional suppliers deliver Albacete using sea freight compared to the current scenario where only Airbus Mexico uses sea freight. For these suppliers additional WIP costs and handling costs incurred when using sea freight are smaller than transportation cost reduction achieved. Total cost is reduced from 66 K€ to 33K€ for them, which represents a 49% total cost reduction in this reduced scope. However, this reduction represents only a 1% supplementary total cost reduction in the global scope compared to the scenario were transportation lot sizes are optimized maintaining current transportation mode constraints.

In the same way, by optimizing transportation lot sizes and including sea freight as an alternative for all the suppliers located in North America, CO_2 emissions are reduced by 33%, from 1277 tons to 862 tons. In fact, when transportation lot sizes are optimized including sea freight as an alternative for all the North America suppliers, 103 tons are delivered using sea freight, compared to 53 tons in the current scenario. Results are presented in Table 5.3 and in Figure 5.2.

Transportation Mode	Tons of CO2 emitted - Current scenario	Tons delivered - Current scenario	Tons of CO2 emitted - Orders grouping + Sea scenario	Tons delivered - Orders grouping + Sea scenario
Air	580	65	105	15
Road	688	1632	737	1632
Sea	10	53	20	103
Total	**1277**	**1750**	**862**	**1750**

Table 5.3. Transportation lot sizing + sea freight inclusion as an alternative for all North America suppliers CO_2 emissions

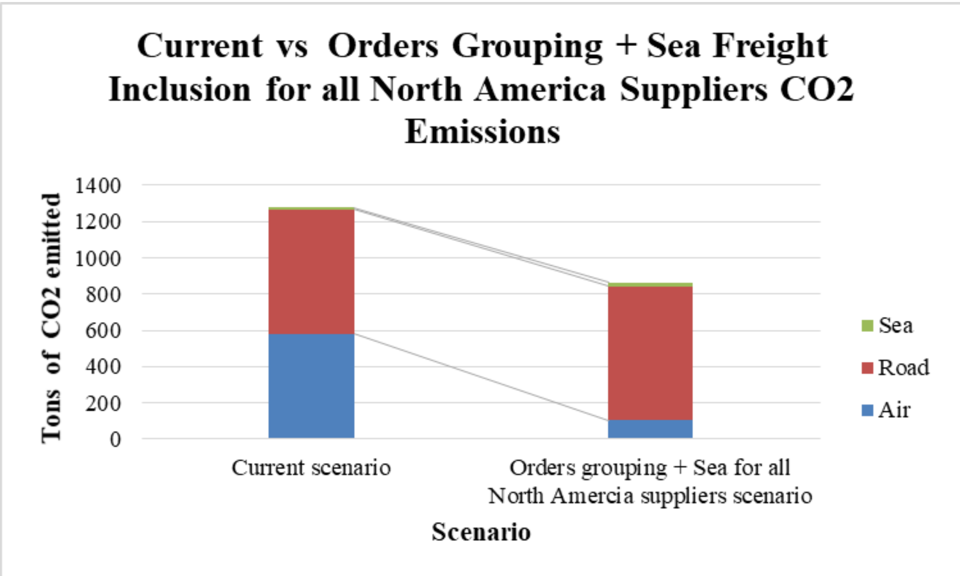

Figure 5.2. Transportation lot sizing + sea freight inclusion as an alternative for all North America suppliers CO_2 emissions

As is shown in Table 5.3, in the second scenario weight delivered using airfreight is reduced while weight delivered using sea freight increases. Weight delivered using road freight remains the same. Concerning road freight CO_2 emissions, they increase in the second scenario because suppliers using sea freight need to deliver parts to the port at New York using road freight, and in order to deliver Albacete, parts need to be transported by road freight from the port of Valencia.

Even if the objective of the models used in this section is cost reduction, solutions obtained reduce CO_2 emissions as well. By optimizing transportation lot sizes, only a transportation and a delivery method is selected per supplier. For 3 suppliers over 15 located in North America, even if using sea freight implies an extra WIP cost due to transportation lead times, using sea freight still being the cheapest option. In other words, results show that sea freight is a cost-efficient and sustainable transportation mode for some suppliers.

5.2. Transportation Lot Sizing, Transportation Mode Selection and Cross Dock Location

In this section, we combine transportation lot sizing, transportation mode selection and cross-dock location optimization axes. To this end, we use the transportation lot sizing model developed in section 3.1.2., including sea freight as an alternative for North American suppliers in order to obtain input costs for the cross-dock location model with storage cost at the cross-docks, presented in section 4.1.4. As a reminder, in this model, there is a set of suppliers, a set of potential cross-docking facilities and a set of warehouses. Suppliers have the option of delivering the cross-docking facilities or delivering directly warehouses. Each alternative has a cost. Hence, there is a cost for each couple supplier – warehouse and supplier – cross-docking facility. In this section, we estimate these costs using the transportation lot-sizing model presented in section 3.1.2. In other words, we define for each couple, an optimal delivery cost. When estimating costs for each couple supplier-cross-docking facility handling cost needs to be included in the transportation lot-sizing model.

In other hand, the cross-dock location model with storage costs at the cross-docks fixes the delivery frequency between the cross-docking facilities and the warehouses. Taking into account this delivery frequency, we treat the optimal delivery frequencies obtained with the transportation lot-sizing model in order to avoid storage at the cross-docking facilities.

In the next section we present how we include handling costs in the transportation lot sizing model in order to estimate input costs for each couple supplier-cross-docking facility, then we define the way in which the optimal delivery frequencies obtained using the transportation lot sizing model are treated in order to avoid storage at the cross-docking facilities. Finally, we present the solution obtained by combining transportation lot sizing, transportation mode selection and cross-dock location.

5.2.1. Transportation Lot Sizing Model with Handling Costs

As a reminder, in this thesis it is assumed that handling cost per pallet is 16€ and that the capacity of a pallet is equal to 1000 kg. Hence handling cost is fixed and equal to 16 € for shipment weights between 0 and 1000 kg, to 32 € for shipment weights between 1000 and 2000 kg and so on. In the section 3.1.2. the total cost for $TC_i(Q)$ for a shipment delivered using PCS whose weight Q is between L_i and U_i is defined as:

$$TC_i(Q) = Cv_iQ + Cc_i + Cs\frac{Q^2}{2D} \qquad if\ L_i < Q \leq U_i \tag{5.1}$$

Where the first part of the function correspond to transportation cost. In the PCS case, transportation cost is defined as a linear function per interval where Cv_i is the slope and Cc_i the intercept of the function. The second part of $TC_i(Q)$ corresponds to the storage cost for the shipment where Cs is the storage cost per kg per year and D is the demand per year. In the case of shipments going from the suppliers to the cross-docking facilities, the handling cost H_i needs to be included in total cost per shipment:

$$TC_i(Q) = Cv_iQ + Cc_i + Cs\frac{Q^2}{2D} + H_i \qquad if\ L_i < Q \leq U_i \tag{5.2}$$

The value of H_i is defined in function of the interval. By dividing $TC_i(Q)$ by Q we obtain the total cost per kg $TC\ per\ kg_i(Q)$.

$$TC\ per\ kg_i(Q) = Cv_i + \frac{Cc_i}{Q} + Cs\frac{Q}{2D} + \frac{H_i}{Q} \qquad if\ L_i < Q \leq U_i \tag{5.3}$$

$TC\ per\ kg_i$ is a convex function, hence we can find the Q_i^* that minimizes the total cost TC_i for the interval i which corresponds to the EOQ:

$$Q_i^* = \sqrt{\frac{2D(Cc_i + H_i)}{Cs}} \qquad if\ L_i < Q \leq U_i \tag{5.4}$$

Concerning the LTL delivery method, we calculate the Q_i^* per interval using the EOQ formula too, by replacing Cc_i with the corresponding LTL transportation cost C_{LTLi} of the interval:

$$Q_i^* = \sqrt{\frac{2D(C_{LTLi} + H_i)}{Cs}} \qquad if\ L_i < Q \leq U_i \tag{5.5}$$

As it is shown in expressions (5.4) and (5.5) the only difference with the Q_i^*obtained in section 3.1.2. is that handling cost per interval H_i is added to transportation cost per interval.

The rest of the model remains the same. If the Q_i^* is less than or equal to the lower bound L_i of the interval, the Q_i^* for the interval must be equal to the lower bound L_i. Similarly, if the Q_i^* is greater than or equal to the upper bound U_i of the interval, the Q_i^* for the interval must be equal to the upper bound U_i. The Q_i^* defines optimal delivery frequencies, which are after approximated to the industrial delivery frequencies defined in section 3.1.2.

5.2.2. Cross-Dock Location - Input Delivery Frequency Modification

Storage costs at the cross-docking facilities are defined in function of delivery frequencies between suppliers and the cross-docking facilities and the fixed delivery frequency between the cross-docking facilities and Albacete. Let us say that there is a supplier S1, and a cross-docking facility CD1. Let us suppose that delivery frequency from S1 to CD1 is F1 and that delivery frequency from CD1 to Albacete is F2 (Figure 5.3.). In the same way, transportation lot size from S1 to CD1 is Q1 and transportation lot size from CD1 to ALB is Q2.

Figure 5.3. F1 and F2 example

If F1 < F2 then we assume that there is no stock at CD1 (it is negligible), but if F1 > F2, parts must be stored at CD1. Let us suppose that in the second case F1 is a multiple of F2:

$$F1 = l * F2 \tag{5.6}$$

Where l is an integer greater than or equal to 1. Then:

$$Q1 = \frac{Q2}{l} \tag{5.7}$$

When F1 >F2 and F1 is a multiple of F2, if we assume that parts are picked up at a constant rate at Albacete, total average inventory at the cross-docking facility and Albacete is:

$$Average\ Inventory\ (CD1 + Albacete) = \frac{Q1}{2} * (2l - 1) \tag{5.8}$$

Taking into account that in our case F2 is fixed, Q2 is fixed too. By replacing Q1 we obtain:

$$Average\ Inventory\ (CD1 + Albacete) = \frac{Q2}{2} * \frac{(2l - 1)}{l} \tag{5.9}$$

In order to illustrate this situation let us say that l = 4. If we assume that transportation lead time is negligible (compared to time that parts are in the stock) between S1 and CD1 and between CD1 and Albacete, inventory evolution in time at S1, CD1 and Albacete can be plotted as in Figure 5.4. In this case:

$$Average\ Inventory\ (CD1 + Albacete) = \frac{Q2}{2} * \frac{7}{4} \tag{5.10}$$

Based on (5.10), if l increases it means that delivery frequency between the supplier and the cross-docking facility increases, and consequently transportation cost and total storage cost too (Albacete + cross docking facility). In this way when F2 is fixed, minimum cost delivery policy is achieved when l = 1 or F1 = F2. Storage cost at the supplier is not taken into account, it is paid by the supplier and it is assumed that it does not affect parts cost.

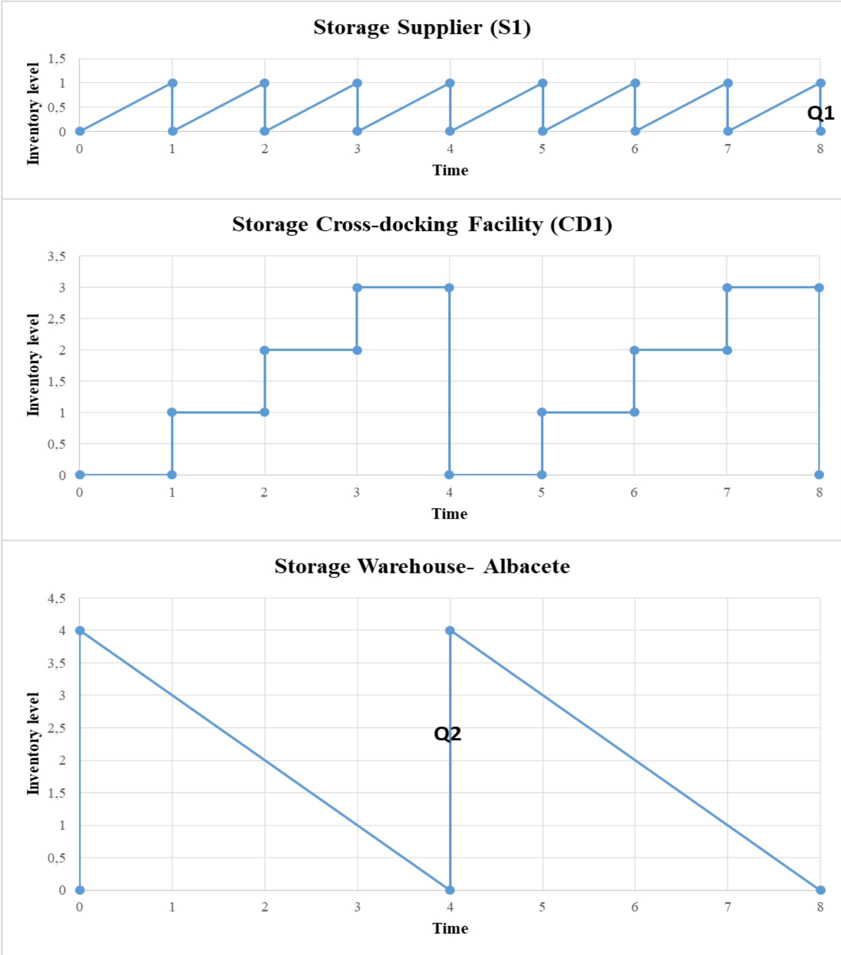

Figure 5.4. Inventory evolution at S1, CD1 and Albacete if F1 = 4*F2

Taking into account these facts, we modify the optimal delivery frequencies obtained with the transportation lot-sizing model for couples supplier - cross-docking facility (in Section 5.2.1) in function of the fixed delivery frequency between the cross-docking facility and Albacete. If the delivery frequency obtained using the transportation lot sizing model between the supplier and the cross-docking facility is bigger than the fixed delivery frequency between the cross-docking facility and Albacete, then the delivery frequency between the supplier and the cross-docking facility is set equal to the fixed delivery frequency between the cross-docking facility and Albacete. In the other hand, if the delivery frequency obtained between the supplier and the cross-docking facility is smaller than the fixed delivery frequency between the cross-docking facility and Albacete, then there is no modifications. Input costs (transportation, storage and handling costs) for the cross-dock location model are estimated taking into account these statements.

Finally, by ensuring that delivery frequencies between suppliers and the cross-docking facilities are always smaller than or equal to the fixed delivery frequency between the cross-docking facilities and Albacete, we can avoid storage costs at the cross-docking facilities.

5.2.3. Solution: Optimized Scenario 1

In this case, we include the same supplier set presented in section 4.1.3 (152 suppliers located in Europe, North America and Morocco). Concerning the cross-docking facilities set, we use the same set presented in section 4.1.3 and we include an additional potential cross-docking facility located in New York. It is supposed that a FTL sea delivery method is used from this cross-docking facility to Albacete. The FTL sea delivery method here makes reference to the fact that we use the full capacity of a container (we assume that the container capacity is 24 tons too). Using shipments for 2018 and the transportation lot sizing model with the modifications presented previously, we obtain the input costs C'_{i0} and C'_{ij} for the cross-dock location model presented in Section 4.1.4. These costs include storage costs, handling costs and transportation costs. In cases where sea freight is selected for a couple source – destination in the transportation lot sizing model, the WIP cost is included too.

As in section 4.1.5., we run the cross-dock location model for different values for the fixed delivery frequency between the cross-docking facilities and Albacete (FTL_{jk}): twice per month, once per week and twice per week. In all these cases, only the cross-docking facility at **Toulouse** is used, assuming that a FTL transportation mode with a capacity of 24 tons is used between the cross-docking facilities and Albacete. In fact, using an additional cross-docking facility implies that a FTL transportation mode should run FTL_{jk} times per year and with the volume delivered the capacity use rate of the FTL transportation mode used in an additional cross-docking facility would be very low. The minimum cost is obtained for FTL_{jk} equal to once per week (48 times per year). Let us call this scenario the **optimized scenario 1**. Results are presented in Table 5.4 and Figure 5.5.

Fixed felivery frequecy between CD Toulouse and Albacete	Total Cost
Twice per month - 24 times per year	1,84 M€
Once per week - 48 times per year	1,83 M€
Twice per week - 96 times per year	1,94 M€

Table 5.4. Total cost results for different values of FTL_{jk}

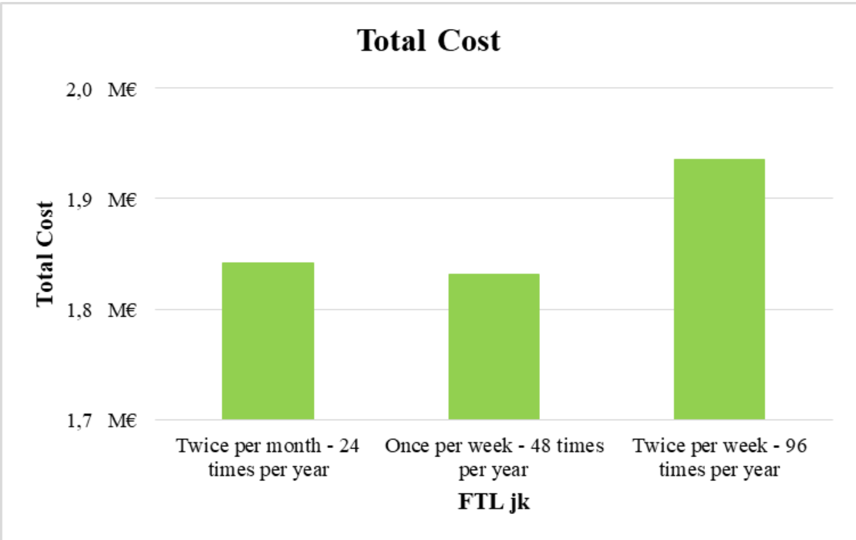

Figure 5.5. Total cost results for different values of FTL_{jk}

Detailed transportation cost, storage cost, handling cost and WIP cost are presented in Table 5.5 and Figure 5.6 for the optimized scenario 1 compared to the current scenario. By optimizing transportation lot sizes, including sea freight for all the North America shipments and using the cross-docking facility at Toulouse with a fixed delivery frequency of 48 times per year between Toulouse and Albacete total cost can be reduced by 44%. A 3% supplementary cost reduction is achieved compared to the scenario where only transportation lot sizing and sea freight inclusion are combined. Cost reduction is mainly due to delivery frequency reduction for 97%

of the suppliers and the consolidation of PCS and LTL shipments in FTL shipments at the cross-docking facility at Toulouse. 107 suppliers over 152 deliver 1152 tons (66% of the total volume) to the cross-docking facility at Toulouse.

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	% Cost Reduction
Current scenario	154 K€	99 K€	3,03 M€	0	3,3 M€	-
Optimized scenario 1	438 K€	124 K€	1,21 M€	62 K€	1,83 M€	-44%

Table 5.5. Optimized scenario 1 vs current scenario cost

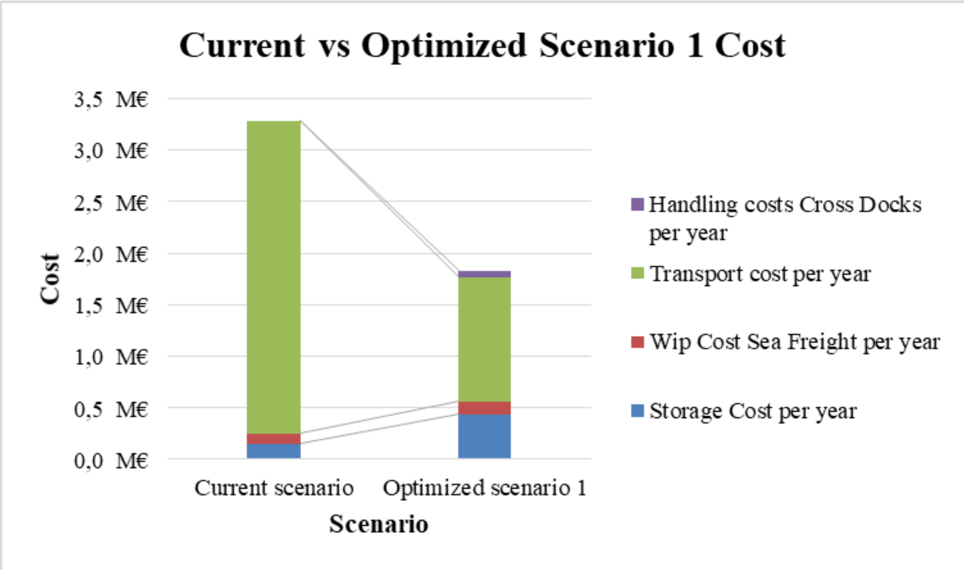

Figure 5.6. Optimized scenario 1 vs current scenario cost

Concerning CO_2 emissions, they are reduced by 45%, from 1277 to 706 tons of CO_2 emitted per year. Total CO_2 emissions per transportation mode for the current and the optimized scenario 1 are presented in Table 5.6 and Figure 5.7. As in the scenario presented in section 5.1 airfreight CO_2 emissions are reduced because the supplier located in Mexico and two suppliers located in United States use sea freight for deliveries when transportation lot sizes are optimized. In the same way, road freight emissions are reduced from 688 tons to 580 tons of CO_2 in the optimized scenario 1. This is due to the fact that the cross-docking facility at Toulouse allows consolidating PCS and LTL shipments in FTL shipments, and the emission factor for a FTL truck is smaller than the emission factors for LTL and PCS transportation modes. In this case, the capacity use rate of the FTL truck used between Toulouse and Albacete is 100% taking into account the volume delivered to Toulouse. Hence, for transportation between Toulouse and Albacete we use the FTL emission factor presented in Section 2.4.2. Regarding cross-docking CO_2 emissions we maintain the hypothesis defined in section 4.1.5. These emissions are negligible compared to transportation emissions.

Source	Tons of CO2 emitted - current scenario	Tons of CO2 emitted - optimized scenario 1
Air	580	105
Road	688	580
Sea	10	20
Cross-Docking	0	1
Total	**1277**	**706**

Table 5.6. Optimized scenario 1 vs current scenario CO_2 emissions

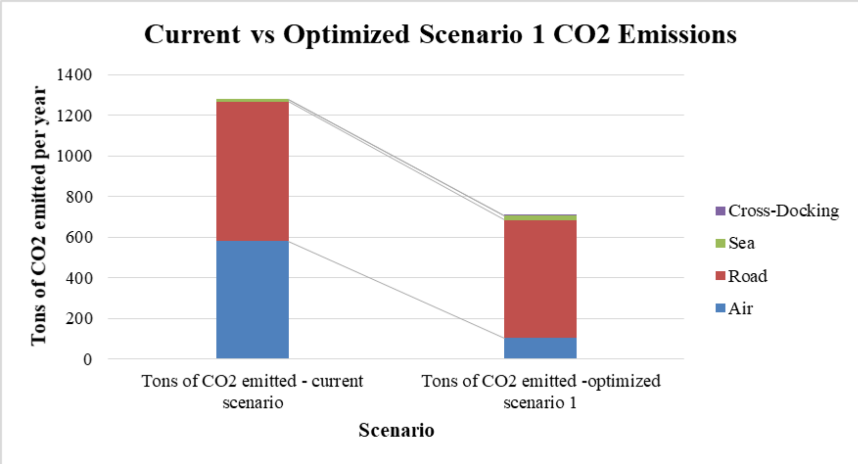

Figure 5.7. Optimized scenario 1 vs current scenario CO_2 emissions

5.2.4. Solution: Optimized Scenario 2

As it was mentioned previously, in the Section 5.2.3, we include an additional potential cross-docking facility at New York and we assume that a FTL sea delivery method with a capacity of 24 tons is used from New York to Albacete; however, total volume delivered per year by suppliers located in North America is equal to 113 tons. Assuming that the fixed delivery frequency between the cross-docking facilities and Albacete is once per week, if the cross-docking facility at New York is used, the maximum volume delivered per week from this facility to Albacete would be 3 tons. This is not enough to use the capacity of a FTL delivery method (24 tons). For this reason in the optimized scenario 1, the cross-docking facility at New York is not used. Taking into account this, we run an **optimized scenario 2.** In the optimized scenario 2, a LTL sea delivery method (only a part of the container is used by Airbus: in order to transport 3 tons per week) is used from the cross-docking facility at New York to Albacete, instead of using a FTL sea deliver method. After running the optimized scenario 2, two cross-docking facilities are used: the cross-docking facility at Toulouse and the cross-docking facility at New York. Total costs for the optimized scenario 2 compared to the current scenario and the optimized scenario 1 are presented in Table 5.7 and Figure 5.8. Figure 5.9 and Figure 5.10 show suppliers allocation. Total cost is reduced by 46% compared to the current scenario. A supplementary 2% cost reduction is achieved compared to the optimized scenario 1. In fact, even if a LTL delivery method is used between the cross-docking facility at New York and Albacete, transportation cost is reduced due to the consolidation of a LTL shipment in the cross-docking facility at New York, which is delivered using sea freight. In total, 8 over 15 suppliers located in North America deliver 104 tons to the cross-docking facility at New York. For these suppliers, supplementary handling costs at the cross-docking facilities, and WIP costs are smaller than transportation cost reduction achieved by the consolidation of LTL sea freight shipments.

Scenario	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	% Cost Reduction
Current scenario	154 K€	99 K€	3,03 M€	0	3,3 M€	-
Optimized scenario 1	438 K€	124 K€	1,21 M€	62 K€	1,83 M€	**-44%**
Optimized scenario 2	451 K€	137 K€	1,13 M€	64 K€	1,78 M€	**-46%**

Table 5.7. Total cost optimize scenarios and current scenario

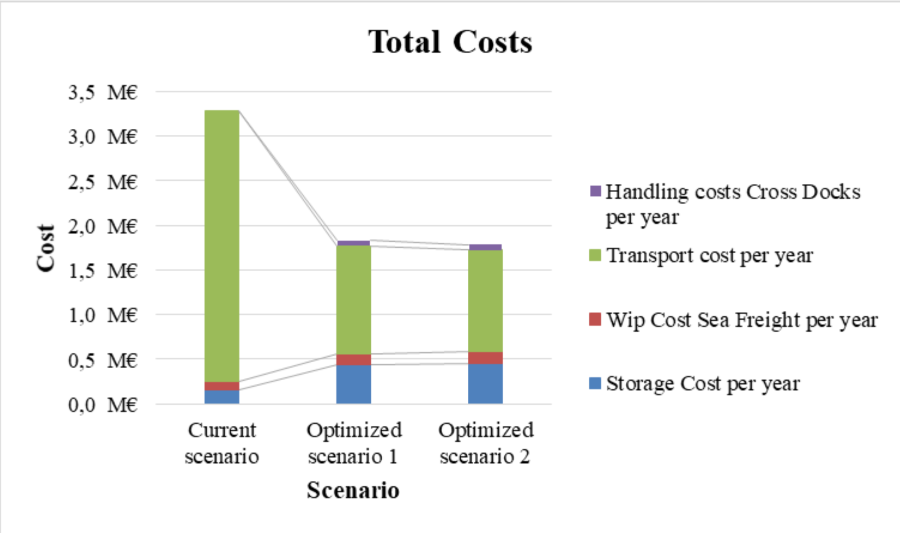

Figure 5.8. Total cost optimize scenarios and current scenario

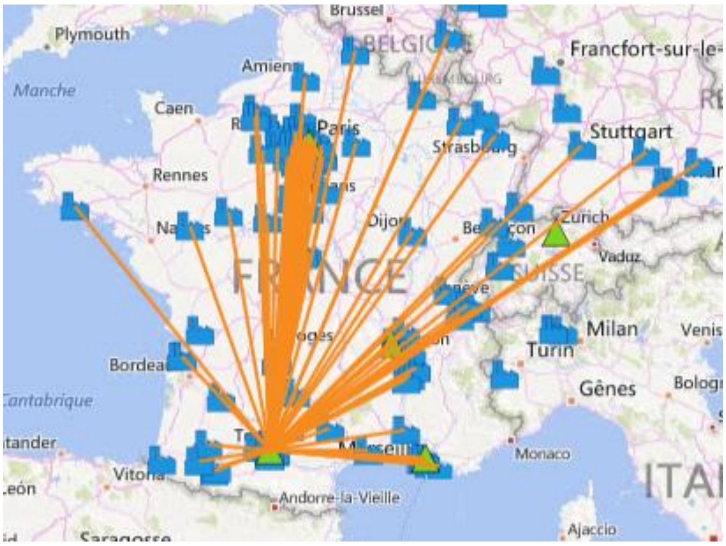

Figure 5.9. Suppliers allocation to the cross-docking facility at Toulouse – Optimized scenario 2

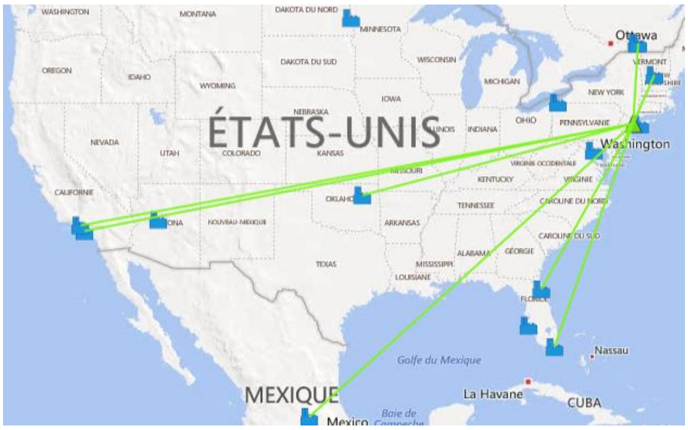

Figure 5.10. Suppliers allocation to the cross-docking facility at New York –Optimized scenario 2

CO_2 emissions are presented for the current scenario, the optimized scenario 1 and the optimized scenario 2 in Table 5.8 and Figure 5.11. A reduction of 47% from 1277 tons to 672 tons of CO_2 emitted per year is achieved in the optimized scenario 2 compared to the current scenario. Compared to the optimized scenario 1, by using the cross-docking facility at New York and using a LTL sea freight transportation mode between it and Albacete, CO_2 emissions are reduced from 706 tons to 672 tons of CO_2 emitted. Supplementary CO_2 emissions reduction achieved in the optimized scenario 2 are due to the fact that 8 suppliers instead of 3 (optimized scenario 1) use sea freight to deliver Albacete, passing through the cross-docking facility at New York. Concerning the cross-docking CO_2 emissions at the New York Facility, we assume that the surface occupied by parts delivered by the suppliers is equal to 3 m^2 (on average 3 pallets are delivered per week from New York to Albacete and the area occupied by 1 pallet is 1 m^2). Concerning the loading, unloading and circulation areas, we assume that they are equal to the base of a semitrailer (13.6 m x 2.55 m). If we maintain the hypothesis presented in Section 4.1.5, CO2 emissions are equal to 0.794 tons per year, which is negligible compared to transportation emissions.

Source	Tons of CO2 emitted - current scenario	Tons of CO2 emitted - optimized scenario 1	Tons of CO2 emitted - optimized scenario 2
Air	580	105	68
Road	688	580	582
Sea	10	20	21
Cross-Docking	0	1	2
Total	**1277**	**706**	**672**

Table 5.8. CO_2 emissions current scenario and optimized scenarios

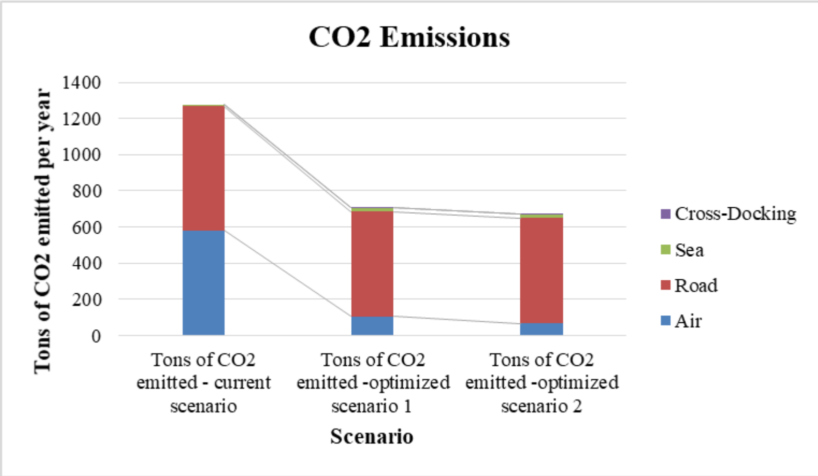

Figure 5.11. CO_2 emissions current scenario and optimized scenarios

5.2.5. Milk Run Evaluation

Using the cross dock location model presented in Section 4.1.4 and the milk run evaluation model presented in Section 4.2.2 we evaluate the implementation of the milk run concept for four scenarios. We define these scenarios based on the milk run evaluation model presented in Section 4.2.2 and taking into account results obtained in the optimized scenario 2 for the cross-dock location model:

1. **Milk run scenario 1:** This scenario evaluates the implementation of the milk run concept including third party shipments for the optimized scenario 2 around the cross-docking facility at Toulouse.

2. **Milk run scenario 2:** This scenario evaluates the implementation of the milk run concept including only the AH shipments for the optimized scenario 2 around the cross-docking facility at Toulouse.

3. **Milk run scenario 3:** As it is shown in section 4.2.3., there is an important concentration of suppliers in the Parisian region. Hence, in this scenario we run the cross-dock location model forcing the suppliers to use the cross-docking facility at Paris and the cross-docking facility at New York. We evaluate the implementation of the milk run concept including third party shipments around the cross-docking facility at Paris.

4. **Milk run scenario 4:** In this scenario, we run the cross-docking location model forcing the suppliers to use the cross-docking facility at Paris and the cross-docking facility at New York. We evaluate the implementation of the milk run concept with only the AH shipments around the cross-docking facility at Paris.

As in the Section 4.2.3, we evaluate the scenarios presented previously for an average speed of 38.9 km/h. If we assume that profit margin for the logistics services provider is 40%, the estimated mean milk run cost is 735€ for an average speed of 38.9 km/h. The capacity of the truck used for the milk runs is supposed to be 13 tons. Additionally, only suppliers in a radius of 80 kilometers are included in the milk runs. There are 11 suppliers within this distance range in the case of Toulouse and 37 suppliers in the case of Paris. All of these suppliers are included in the milk runs. Taking into account the fixed delivery frequency between the cross-docking facilities and Albacete, it is assumed that milk runs take place 48 times per year in all the scenarios. Storage costs and handling costs are calculated for the suppliers included in the milk run taking into account this frequency. For the scenarios 2 and 4, it is assumed that a maximum of 7 suppliers can be included per milk run. We compare the milk run scenarios with the optimized scenario 2 presented in the Section 5.2.3 and an optimized scenario 3 in which we run the cross-docking location model forcing the suppliers to deliver Paris and New York. Results are presented in Table 5.9

Total costs - Average Speed = 38.9 km/h					
Scenario	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**
Optimized scenario 2	451 K€	137 K€	1,13 M€	64 K€	**1,78 M€**
Optimized scenario 3	475 K€	137 K€	1,2 M€	62 K€	**1,88 M€**
Milk run scenario 1	447 K€	137 K€	1,12 M€	68 K€	**1,77 M€**
Milk run scenario 2	447 K€	137 K€	1,19 M€	68 K€	**1,84 M€**
Milk run scenario 3	464 K€	137 K€	1,13 M€	72 K€	**1,80 M€**
Milk run scenario 4	464 K€	137 K€	1,32 M€	72 K€	**1,99 M€**

Table 5.9. Milk run evaluation – average speed = 38.9 km/h

In the milk run scenarios 2, 3 and 4 total cost increase compared to the optimized scenario 2 and in the milk run scenario 1 total cost is reduced by 12 K€ per year compared to the optimized scenario 2. In the milk run scenarios 1 and 2, only 11 over 152 suppliers are included in the milk run. Volume delivered by these suppliers is only 15 tons per year (1% of the total volume). For this reason, cost reduction achieved in the milk run scenario 1 is not significant. Additionally, implementing milk runs requires a planning effort (hiring one person in order to manage milk runs), which costs more than the reduction achieved. Similarly, in the milk run scenario 2 volume delivered by the suppliers is not enough to implement the milk run concept including only the AH shipments in a cost-efficient way. It increases cost from 1.78 M€ to 1.84 M€.

In the other hand, by moving the cross docking facility from Toulouse to Paris without implementing the milk run concept, total cost is increased from 1.78 M€ to 1.88 M€ (optimized scenario 3). Even if by implementing the milk run concept including third party shipments, total cost is reduced from 1.88 M€ to 1.80 M€ in the milk run scenario 3, it stills being more expensive than the optimized scenario 2 (1.78 M€). As for the milk run scenario 2, in the milk run scenario 4, volume delivered by the suppliers is not enough to implement the milk run concept with a frequency of once per week including only the AH shipments in a cost-efficient way. It increases cost from 1.88 M€ to 1.99 M€. In these cases, 37 suppliers over 152 that deliver 413 tons per year are included in the milk runs.

Even in the milk run scenario 1, which is a very optimistic scenario, cost reduction achieved using the milk run concept is not significant. In the milk run scenario 1, we assume that the logistics services provider is able to include third party shipments in a way that the milk run capacity is 100% used. Only 15 tons are delivered per year by suppliers included in the milk run. Taking into account that the truck capacity is 13 tons and that delivery frequency is 48 times per year, the total available capacity per year is equal to 624 tons. This means that in the milk run scenario 1 the logistics services provider needs to include 611 tons per year of third party shipments in order to fully use capacity. This may not be feasible in reality. However, the milk run scenario 1 allows demonstrating that even in one of the best scenarios cost reduction achieved by implementing a milk run strategy at Toulouse is not important. Regarding the milk run scenario 3, even if for a cross-docking facility at Paris, cost reduction achieved by implementing a milk run strategy including third party shipments may be profitable compared to the direct delivery scenario (optimized scenario 3), it stills being cheaper to keep the cross-docking facility at Toulouse without implementing milk runs.

In conclusion, implementing the milk run strategy for the AH case is not profitable from a cost point of view due to small delivery volumes included in this study and the small number of suppliers around the cross-docking facility at Toulouse.

5.2.6. Conclusion

In this section, we combine the transportation lot sizing model, the transportation mode selection model and the cross-dock location model presented in chapters 3 and 4 in order to build a cost-efficient transportation solution for the AH case**. As a result, by optimizing transportation lot sizes, including sea freight in transportation mode alternatives for North America suppliers and using the two cross docking facilities at Toulouse and New York total cost and CO_2 emissions could be potentially reduced by 46% and 47% respectively (optimized scenario 2).**

Cost reduction is due mainly to delivery frequency reduction for suppliers and shipment consolidation. In the current scenario, transportation lot sizes are defined only in function of storage costs, which results in big delivery frequencies and small shipment sizes. By including transportation cost in transportation lot sizes optimization, delivery frequency is reduced for 97% of the suppliers. Additionally, the cross docking facility at Toulouse allows consolidating road PCS and LTL shipments in road freight FTL shipments and the cross-docking facility at New York allows consolidating road LTL and PCS shipments in sea freight LTL shipments. LTL sea freight and FTL road freight transportation modes have lower emission factors than road freight PCS, LTL and air freight transportation modes, which explains CO_2 emissions reduction.

Additionally, by using the milk run evaluation model presented in section 4.2.2., it is shown that a milk run strategy around the cross-docking facilities is not profitable for AH due to small delivery volumes.

Despite the small delivery volumes in the aeronautic industry, results obtained show that by optimizing transportation lot sizes and transportation mode selection, and by implementing cross-docking facilities in the AH inbound supply chain or in general in supply chains similar to the AH supply chain (see Table 2.16 in Chapter 2), it is possible to reduce logistics cost significantly. Thus, from a cost point of view, it is recommendable to implement a transport organization that allows controlling and optimizing inbound transportation in the aeronautic industry.

Regarding the environmental dimension, as it was mentioned before, it is not included explicitly in models used in this chapter. However, by optimizing cost, CO_2 emissions are reduced by 47%. Hence cost optimization is also a first step towards a sustainable inbound supply chain. In the next section, we will conduct a sensitivity analysis on the input costs used for the optimization models in order to evaluate the robustness of the results obtained in the optimized scenario 2.

Finally, as it was mentioned in Section 4.1.2, due to small delivery volumes included in this study we do not include the capacity of the cross-docking facilities. We assume that they are able to deal with all the deliveries. However, for a larger perimeter, it would be necessary to take them into account. All we need to do is to include an additional constraint in the cross-dock location model: constraint (5.11), where $Capacity_j$ is the capacity of the cross-docking facility j.

$$\sum_{i=1}^{n}\sum_{k=1}^{p} X_{ij}V_{ik} \leq Capacity_j \qquad \forall j \in M \tag{5.11}$$

5.3. Sensitivity analysis

In this section, we present a sensitivity analysis on transportation costs, storage costs and handling costs per pallet at the cross-docking facilities. These input parameters have been estimated by defining different hypothesis and it is interesting to check the potential influence of these approximations.

5.3.1. PCS and LTL Transportation Costs

In this study, PCS and LTL transportation costs are defined based on UPS and DHL costs retrieved online. However, in reality, these costs may vary in function of the transportation provider. For that reason, we conduct a sensitivity analysis on these costs. Firstly, we analyze impact on the total cost reduction achieved and the cross-docking facilities used. Results are presented in Tables 5.10, 5.11, 5.12, 5.13, 5.14 and 5.15 and in Figures 5.12 and 5.13. **In Tables 5.10, 5.11 and 5.12, and Figure 5.12 we evaluate PCS and LTL costs increase**. We present results obtained when the PCS and LTL costs are multiplied by 3, 5 and 7 in order to show at which point cross-docking facilities used change. If the PCS and LTL costs are multiplied by 3, then, the cost reduction achieved in the optimized scenario 2 increases from 46% (Table 5.7) to 70% (Table 5.10) and the same cross-docking facilities are used. If the PCS and LTL costs are multiplied by 5, then, the cost reduction achieved in the optimized scenario 2 increases from 46% (Table 5.7) to 77% (Table 5.11) and the same cross-docking facilities are used. If the PCS and LTL costs are multiplied by 7 then, the cost reduction achieved in the optimized scenario 2 is increased from 46% (Table 5.7) to 80% (Table 5.12). In this case, the cross-docking facility at Saint Etienne is used instead of using the cross-docking facility at Toulouse. As expected, when the transportation PCS and LTL costs increase, the cost reduction achieved by optimizing transportation lot sizes (reducing delivery frequencies) increase significantly, given that the current scenario is characterized by big delivery frequencies and small shipment sizes. Moreover, when PCS and LTL costs are multiplied by 7, the cross-docking facility at Saint Etienne is used instead of using the cross-docking facility at Toulouse even if FTL transportation cost from Toulouse to Albacete is cheaper. This is due to the fact that when PCS and LTL cost are increased, costs between suppliers and the cross docking facilities become more important compared to FTL transportation costs from the cross-docking facilities to Albacete. Furthermore, volume delivered to the cross-docking facilities decrease when PCS and LTL costs increase (from 1256 tons in the optimized scenario 2 with the current PCS and LTL costs to 611 tons when PCS and LTL costs are multiplied by 7), and inversely, volume delivered directly using the FTL delivery method increase (from 452 tons in the optimized scenario 2 with the current PCS and LTL costs to 1135 tons when PCS and LTL costs are multiplied by 7).

In Tables 5.13, 5.14 and 5.15 and in Figure 5.13 we evaluate PCS and LTL transportation costs reduction. If the PCS and LTL costs are reduced by 10%, then, the cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 43% (Table 5.13). If the PCS and LTL costs are reduced by 20%, then, the cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 40% (Table 5.14). Finally, if the PCS and LTL costs are reduced by 30%, then, the cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 36% (Table 5.15).

PCS, LTL Cost x 3								
Scenario	CDS Used	Volume delivered per year to the CDS (Tons)	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	-	154 K€	99 K€	8,25 M€	0	8,5 M€	0%
Optimized scenario 2	Toulouse, New York	921	720 K€	227 K€	1,6 M€	47 K€	2,59 M€	70%

Table 5.10. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by three

PCS, LTL Cost x 5								
Scenario	CDS Used	Volume delivered per year to the CDS (Tons)	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	-	154 K€	99 K€	13,31 M€	0	13,6 M€	0%
Optimized scenario 2	Toulouse, New York	646	999 K€	227 K€	1,9 M€	34 K€	3,16 M€	77%

Table 5.11. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by five

PCS, LTL Cost x 7								
Scenario	CDS Used	Volume delivered per year to the CDS (Tons)	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	-	154 K€	99 K€	18,27 M€	0	18,5 M€	0%
Optimized scenario 2	Saint Etienne, New York	611	1,13 M€	227 K€	2,24 M€	29 K€	3,6 M€	80%

Table 5.12. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by seven

PCS, LTL Cost x 0,9								
Scenario	CDS Used	Volume delivered per year to the CDS (Tons)	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	-	154 K€	99 K€	2,76 M€	0	3,01 M€	0%
Optimized scenario 2	Toulouse, New York	1254	433 K€	137 K€	1,08 M€	66 K€	1,72 M€	43%

Table 5.13. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by 0.9

PCS, LTL Cost x 0,8								
Scenario	CDS Used	Volume delivered per year to the CDS (Tons)	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	-	154 K€	99 K€	2,49 M€	0	2,74 M€	0%
Optimized scenario 2	Toulouse, New York	1255	419 K€	137 K€	1,03 M€	67 K€	1,66 M€	40%

Table 5.14. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by 0.8

PCS, LTL Cost x 0,7									
Scenario	**CDS Used**	**Volume delivered per year to the CDS (Tons)**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	-	154 K€	99 K€	2,21 M€	0	2,47 M€	0%
Optimized scenario 2	Toulouse, New York	1249	401 K€	127 K€	993 K€	68 K€	1,59 M€	36%

Table 5.15. Current scenario and optimized scenario 2 cost – PCS and LTL costs multiplied by 0.7

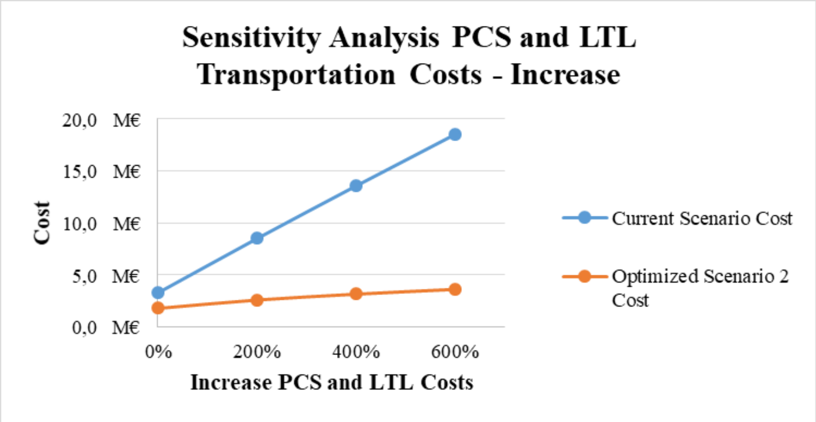

Figure 5.12. Current scenario and optimized scenario 2 cost – PCS and LTL costs sensitivity analysis – Increase

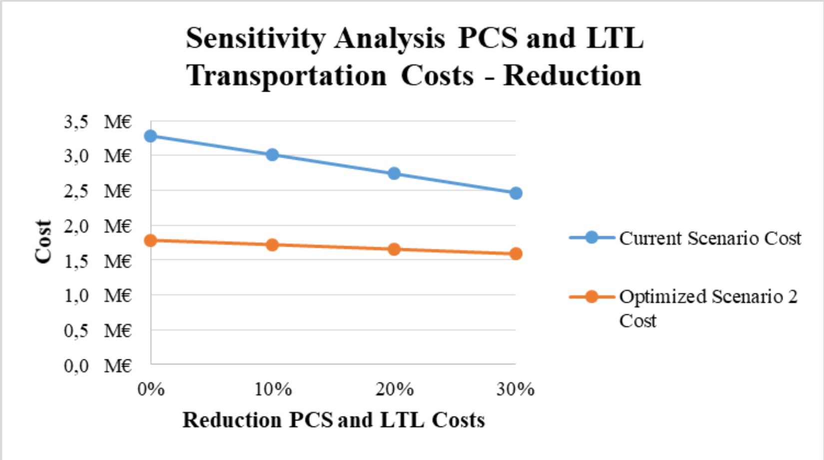

Figure 5.13. Current scenario and optimized scenario 2 cost – PCS and LTL costs sensitivity analysis - Reduction

Secondly, we analyze impact of PCS and LTL costs modification on delivery frequencies obtained for each couple source destination. Results are presented in Figures 5.14 and 5.15. In Figure 5.14, we show delivery frequencies (per year) distribution for each one of the PCS and LTL costs scenarios and in Figure 5.15 we show the total number of deliveries per year for all the suppliers for each scenario as well. As expected, when PCS, and LTL costs increase, delivery frequencies are reduced, and inversely, when PCS, and LTL costs decrease, delivery frequencies are increased. Particularly, when PCS and LTL costs are multiplied by 7, the total number of deliveries per year is reduced by 56% and delivery frequency decreases for 86% of the suppliers. When PCS and LTL costs are reduced by 30%, the total number of deliveries per year is increased by 11% and delivery frequency is increased for 20% of the suppliers.

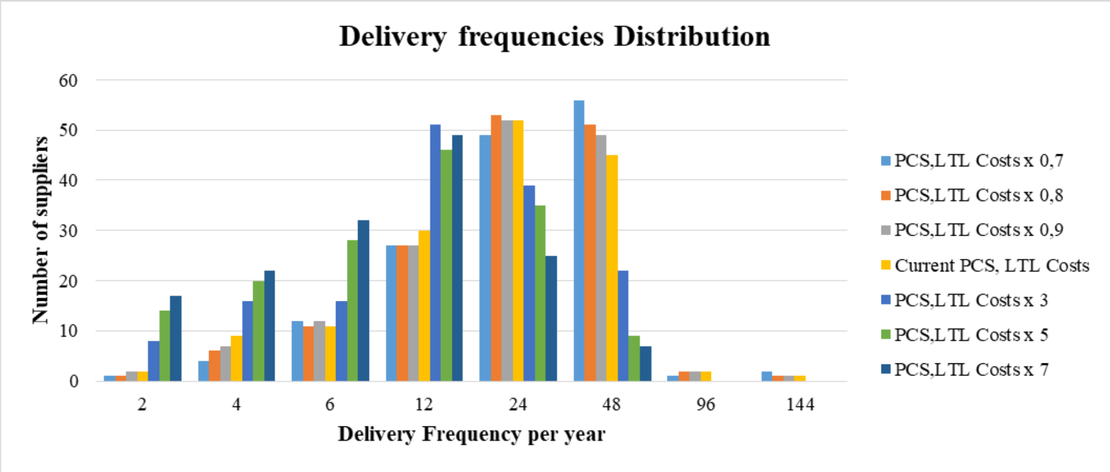

Figure 5.14. Delivery frequencies per year distribution per PCS and LTL costs scenario

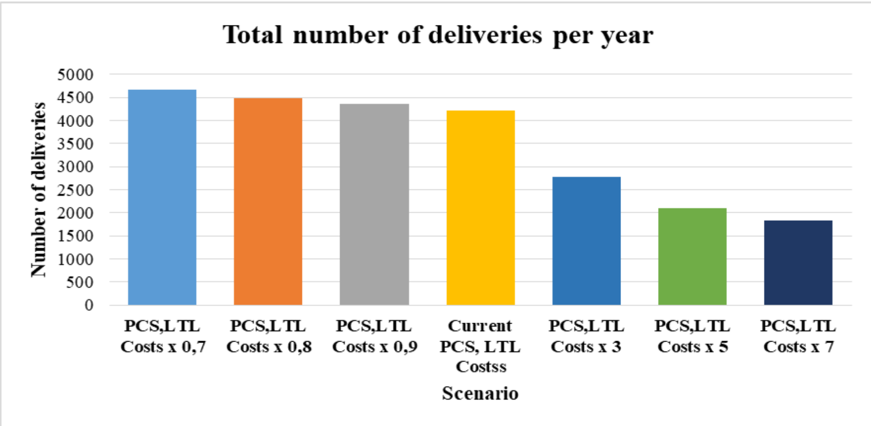

Figure 5.15. Total number of deliveries per year for all the suppliers per PCS and LTL costs scenario

In conclusion, an increase of PCS and LTL transportation costs increases cost reduction potential achieved thanks to delivery frequencies reduction in the optimized scenario 2 and inversely a reduction of PCS and LTL transportation costs decreases cost reduction potential achieved with transportation lot sizes optimization. Regarding the cross-docking facilities used, they change only when PCS, and LTL costs are multiplied by 7 or more. When PCS and LTL costs are multiplied by 7, the cross-docking facility at Saint Etienne is used instead of using the cross-docking facility at Toulouse. Finally, concerning delivery frequencies, when PCS and LTL costs increase, delivery frequencies obtained are reduced and when PCS and LTL costs decrease delivery frequencies obtained increase, as expected.

5.3.2. FTL Transportation Costs between the Cross-docking Facilities and Albacete

FTL transportation costs between the cross-docking facilities and Albacete for this study are estimated based on tariffs provided by Daher. However, these tariffs may vary in reality in function of the transportation provider. For this reason, we conduct a sensitivity analysis on these costs. **Results are presented in Tables 5.16, 5.17, 5.18 and 5.19, and Figures 5.16 and 5.17**.

When FTL costs are increased by 50% total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 43% (Table 5.16) and the same cross-docking facilities are used. When FTL costs are multiplied by two, no cross-docking facilities are used, and the total cost achieved in the optimized scenario 2 corresponds to the total cost achieved when transportation lot sizes are optimized and sea freight is included as an alternative for all the North America shipments (Table 5.17).

In the other hand, when FTL costs are reduced by 20% total cost reduction achieved in the optimized scenario 2 is increased from 46% (Table 5.7) to 47% (Table 5.18) and the same cross-docking facilities are used. When FTL costs are reduced by 50% total cost reduction achieved in the optimized scenario 2 is increased from 46% (Table 5.7) to 49% (Table 5.19) and the same cross-docking facilities are used. Additionally, volume delivered to the cross-docking facilities with the current FTL costs (1256 tons) is maintained when FTL costs are increased by 50% and when FTL costs are reduced by 20% and 50%.

FTL Cost x 1.5							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	Toulouse, New York	451 K€	137 K€	1,23 M€	64 K€	1,88 M€	43%

Table 5.16. Current scenario and optimized scenario 2 cost – FTL costs between the cross-docking facilities and Albacete multiplied by 1.5

FTL Cost x 2							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	No CD used	599 K€	124 K€	1,22 M€	0	1,95 M€	41%

Table 5.17. Current scenario and optimized scenario 2 cost – FTL costs between the cross-docking facilities and Albacete multiplied by 2

FTL Cost x 0,8							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	Toulouse, New York	451 K€	137 K€	1,09 M€	64 K€	1,75 M€	47%

Table 5.18. Current scenario and optimized scenario 2 cost – FTL costs between the cross-docking facilities and Albacete multiplied by 0.8

FTL Cost x 0,5							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	Toulouse, New York	451 K€	137 K€	1,03 M€	64 K€	1,69 M€	49%

Table 5.19. Current scenario and optimized scenario 2 cost – FTL costs between the cross-docking facilities and Albacete multiplied by 0.5

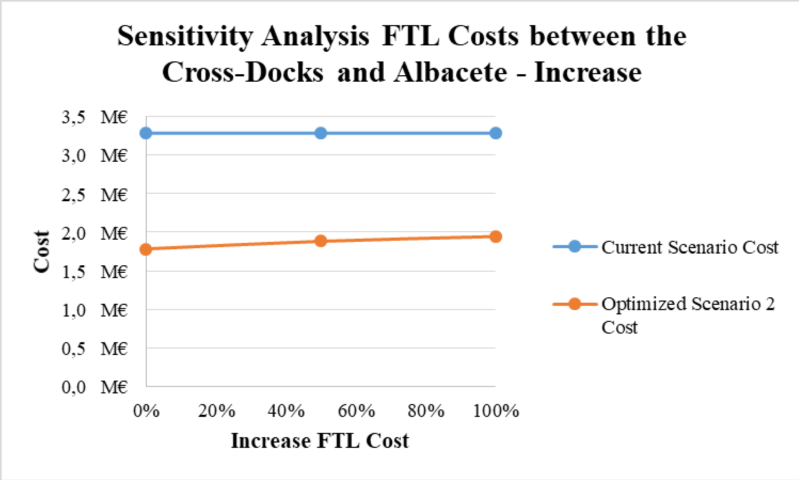

Figure 5.16. Current scenario and optimized scenario 2 cost – FTL costs sensitivity analysis – Increase

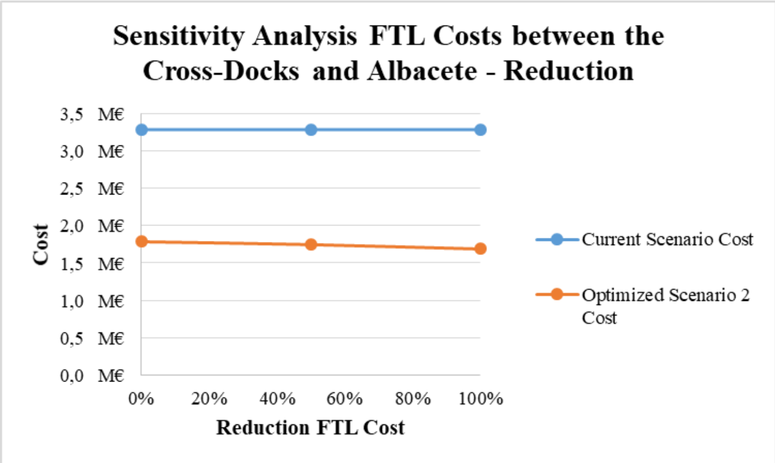

Figure 5.17. Current scenario and optimized scenario 2 cost – FTL costs sensitivity analysis - Reduction

Delivery frequencies for each couple source-destination do not change, given that only FTL transportation costs between the cross-docking facilities and Albacete are modified.

In conclusion, results obtained in the cross-dock location model are sensible to changes in the FTL transportation costs between the cross-docking facilities and Albacete. If they increase by 100%, all the suppliers prefer to deliver directly Albacete without using the cross-docking facilities.

5.3.3. FTL, PCS and LTL Transportation Costs

In this section, we evaluate the impact on results obtained if all the transportation tariffs (PCS, LTL and FTL) increase. Firstly, we analyse the impact on the potential cost reduction achieved and the cross-docking facilities used. **Results are presented in Tables 5.20, 5.21 and 5.22 and Figure 5.18**. If transportation costs increase by 50%, then the total cost reduction achieved in the optimized scenario 2, increases from 46% (Table 5.7) to 54% (Table 5.20). If transportation costs are multiplied by 2, then the total cost reduction achieved in the optimized scenario 2, increases from 46% (Table 5.7) to 58% (Table 5.21). If transportation costs are multiplied by 3 then the total cost reduction achieved in the optimized scenario 2, increases from 46% (Table 5.7) to 64% (Table 5.22). In all the cases, the same cross-docking facilities are used. Volume delivered to the cross-docking facilities is reduced from 1256 tons (current transportation tariffs) to 1220 tons when PCS, LTL and FTL costs are multiplied by 3.

FTL, LTL, PCS Transportation costs x 1.5							
Scenario	CDS Used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	154 K€	99 K€	4,4 M€	0	4,66 M€	0%
Optimized scenario 2	Toulouse, New York	588 K€	161 K€	1,36 M€	59 K€	2,17 M€	54%

Table 5.20. Current scenario and optimized scenario 2 cost – Transportation costs multiplied by 1.5

FTL, LTL, PCS Transportation costs x 2							
Scenario	CDS Used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	154 K€	99 K€	5,78 M€	0	6,03 M€	0%
Optimized scenario 2	Toulouse, New York	637 K€	176 K€	1,65 M€	56 K€	2,51 M€	58%

Table 5.21. Current scenario and optimized scenario 2 cost – Transportation costs multiplied by 2

FTL, LTL, PCS Transportation costs x 3							
Scenario	CDS Used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	Reduction
Current scenario	-	154 K€	99 K€	8,53 M€	0	8,78 M€	0%
Optimized scenario 2	Toulouse, New York	701 K€	227 K€	2,19 M€	52 K€	3,17 M€	64%

Table 5.22. Current scenario and optimized scenario 2 cost – Transportation costs multiplied by 3

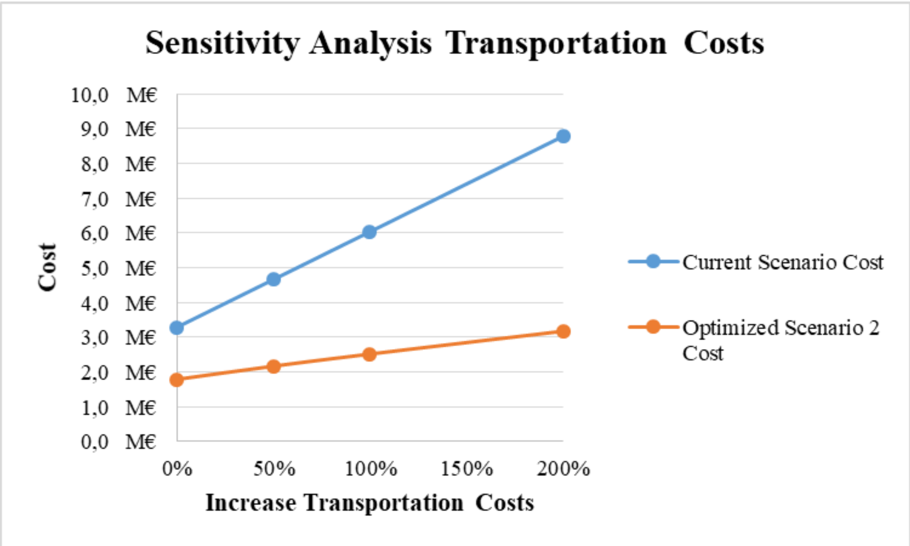

Figure 5.18. Current scenario and optimized scenario 2 cost – Transportation costs sensitivity analysis

Secondly, we analyze impact of PCS, LTL and FTL costs increase on delivery frequencies obtained for each couple source destination. Results are presented in Figures 5.19 and 5.20. In Figure 5.19, we show delivery frequencies (per year) distribution for each one of the PCS, LTL and FTL costs scenarios and in Figure 5.20 we show the total number of deliveries per year for all the suppliers for each scenario as well. As expected, when PCS, and LTL costs increase, delivery frequencies are reduced. Particularly, when PCS and LTL costs are multiplied by 3, the total number of deliveries per year is reduced by 33% and delivery frequency decreases for 59% of the suppliers.

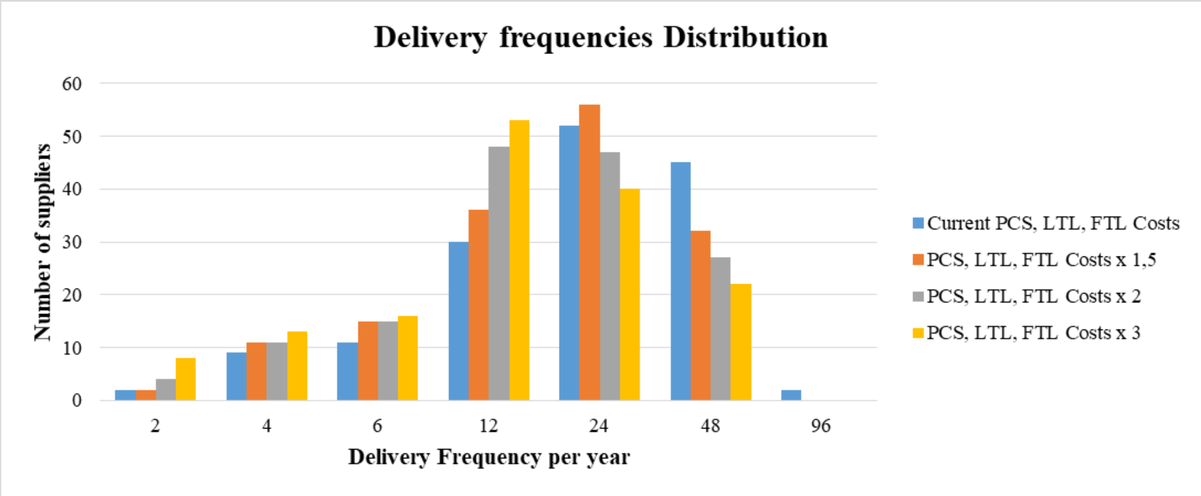

Figure 5.19. Delivery frequencies per year distribution per PCS, LTL and FTL costs scenario

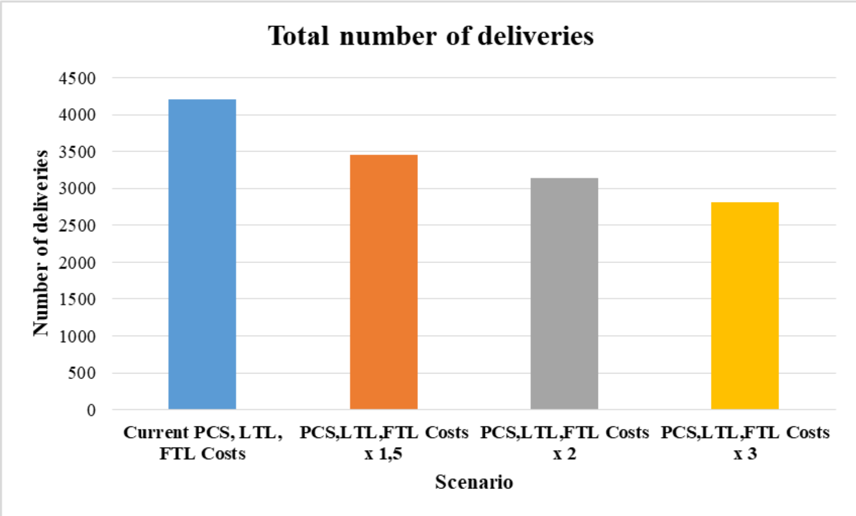

Figure 5.20. Total number of deliveries per year for all the suppliers per PCS, LTL and FTL costs scenario

As expected, an increase of transportation costs increases cost reduction potential achieved thanks to delivery frequencies reduction in the optimized scenario 2. In this case, even if FTL costs between the cross-docking facilities and Albacete are multiplied by 2 or 3, the same cross-docking facilities are used, given that PCS and LTL costs increase too. In this section, we do not analyse transportation costs reduction, the same conclusions presented in Section 5.3.1 would be obtained.

5.3.4. Storage Cost

In this section, we conduct a sensitivity analysis on storage costs. In this study, we assume that storage cost is equal to 10% of parts cost, however this cost may be greater in reality. Firstly, we analyze impact on total cost reduction achieved and the cross-docking facilities used. **Results are presented in Tables 5.23, 5.24, 5.25 and 5.26, and in Figure 5.21.**

When storage cost is increased by 25%, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 42% (Table 5.23). Total costs for the current scenario and the optimized scenario 2 increase by 2% and 8% respectively and the same cross-docking facilities are used.

When storage cost is increased by 50%, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 40 % (Table 5.24). Total costs for the current scenario and the optimized scenario 2 increase by 4% and 15% respectively and the same cross-docking facilities are used.

When storage cost is multiplied by two, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 35% (Table 5.25). Total costs for the current scenario and the optimized scenario 2 increase by 8% and 29% respectively and the same cross-docking facilities are used.

In fact, when storage cost increases, transportation lot sizes are reduced, and delivery frequency increases, for that reason there is an increase on transportation costs and handling costs. In the same way, given that transportation lot sizes are reduced, volume delivered using PCS increases as well: from 110 tons per year in the current case to 151 tons per year when storage cost is multiplied by 2 (Table 5.26). Regarding the volume delivered to the cross-docking facilities, it is reduced from 1256 tons to 1249 tons when storage costs are multiplied by two.

Storage Cost * 1.25							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	192 K€	124 K€	3,03 M€	0	3,35 M€	0%
Optimized scenario 2	Toulouse, New York	523 K€	171 K€	1,16 M€	68 K€	1,93 M€	42%

Table 5.23.Current scenario and optimized scenario 2 cost – Storage cost multiplied by 1.25

Storage Cost x 1.5							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	231 K€	149 K€	3,03 M€	0	3,4 M€	0%
Optimized scenario 2	Toulouse, New York	580 K€	190 K€	1,22 M€	71 K€	2,06 M€	40%

Table 5.24. Current scenario and optimized scenario 2 cost – Storage cost multiplied by 1.5

Storage Cost x 2							
Scenario	**CDS Used**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	308 K€	199 K€	3,03 M€	0	3,5 M€	0%
Optimized scenario 2	Toulouse, New York	694 K€	250 K€	1,29 M€	73 K€	2,3 M€	35%

Table 5.25. Current scenario and optimized scenario 2 cost – Storage cost multiplied by 2

Scenario	**Current Storage Cost**	**Storage Cost x 1.25**	**Storage Cost x 1.5**	**Storage Cost x 2**
Volume delivered using PCS per year	110	117	140	151
Volume delivered using LTL per year	1358	1351	1327	1317
Volume delivered using FTL per year	283	283	283	283
Total	1750	1750	1750	1750

Table 5.26. Volume delivered per delivery method - Storage cost sensitivity analysis

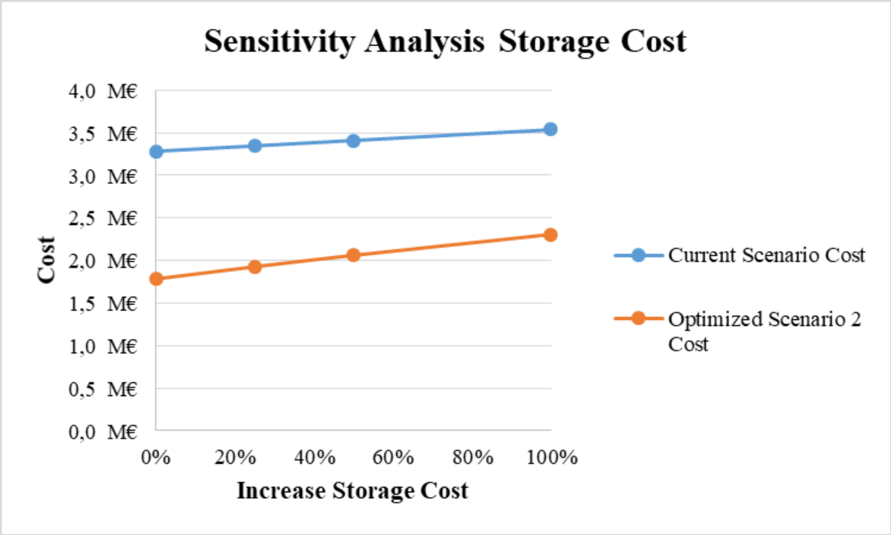

Figure 5.21. Current scenario and optimized scenario 2 cost – Storage cost sensitivity analysis

As it was mentioned before, when storage cost increases, the delivery frequency increases. In Figure 5.22 we present deliveries frequencies distribution per storage cost scenario, and in Figure 5.23 we show total number of deliveries per year for each scenario as well. When storage cost is multiplied by two, total number of deliveries increases by 30% and delivery frequency increases for 44% of the suppliers.

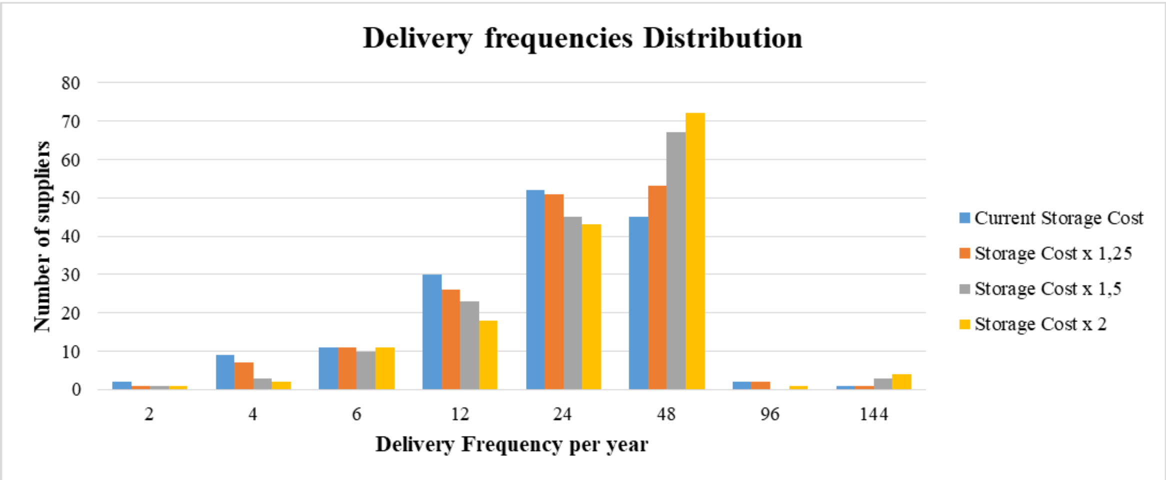

Figure 5.22. Delivery frequencies per year distribution per storage cost scenario

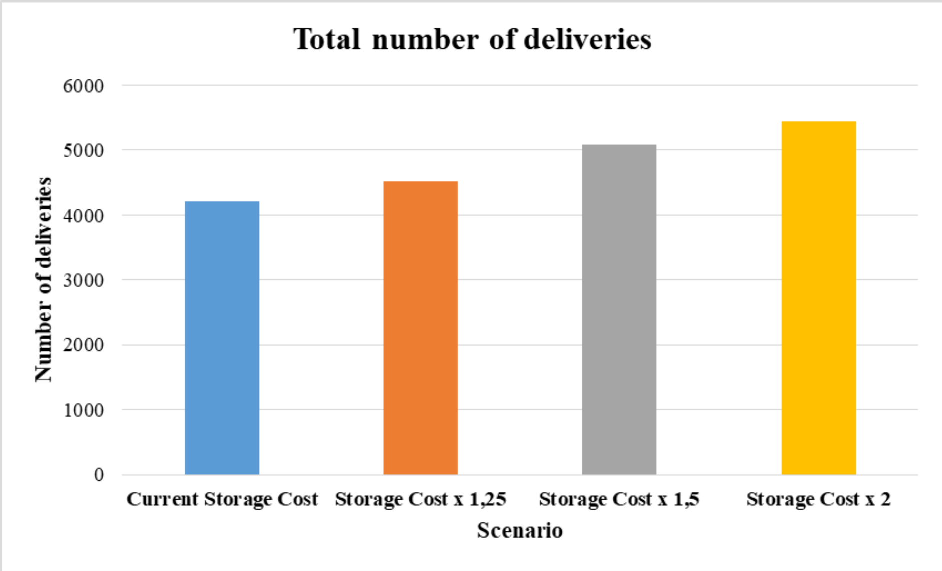

Figure 5.23. Total number of deliveries per year for all the suppliers per storage cost scenario

In conclusion, when storage costs are increased total cost reduction achieved in the optimized scenario 2 decreases slightly and the same cross-docking facilities are used. Concerning delivery frequencies, as expected, when storage costs increase, they increase as well.

5.3.5. Handling Cost

Based on figures provided by the logistics department, in this study we have assumed that handling cost per pallet at the cross-docking facilities is equal to 16,51€. However, this cost may be greater in reality in function of the volume treated at the cross-docking facilities. For that reason, we conduct a sensitivity analysis on this cost. Firstly, we analyse impact on total cost reduction achieved and the cross-docking facilities used. **Results are presented in Tables 5.27, 5.28 and 5.29 and Figure 5.24**.

When handling cost is multiplied by two, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 44% (Table 5.27). Same cross-docking facilities are used and total cost for the optimized scenario 2 increases by 3%.

When handling cost is multiplied by three, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 42% (Table 5.28). Same cross-docking facilities are used and total cost for the optimized scenario 2 increases by 6%.

Finally, when handling cost is multiplied by four, total cost reduction achieved in the optimized scenario 2 is reduced from 46% (Table 5.7) to 42% (Table 5.29). Only the cross-docking facility at New York is used and total cost for the optimized scenario 2 increases by 7%. Volume delivered to the cross-docking facilities is reduced from 1256 tons to 1254 tons when handling cost is multiplied by 3 and it is reduced from 1256 tons to 104 tons when handling cost is multiplied by 4.

Handling Cost x 2							
Scenario	**CDS Opened**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	Toulouse, New York	501 K€	137 K€	1,09 M€	112 K€	1,84 M€	44%

Table 5.27. Current scenario and optimized scenario 2 cost – Handling cost multiplied by 2

Handling Cost x 3							
Scenario	**CDS Opened**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	Toulouse, New York	521 K€	137 K€	1,09 M€	150 K€	1,9 M€	42%

Table 5.28. Current scenario and optimized scenario 2 cost – Handling cost multiplied by 3

Handling Cost x 4							
Scenario	**CDS Opened**	**Storage Cost per year**	**Wip Cost Sea Freight per year**	**Transport cost per year**	**Handling costs Cross Docks per year**	**Total Cost per year**	**Reduction**
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	0%
Optimized scenario 2	New York	613 K€	137 K€	1,15 M€	10 K€	1,9 M€	42%

Table 5.29. Current scenario and optimized scenario 2 cost – Handling cost multiplied by 4

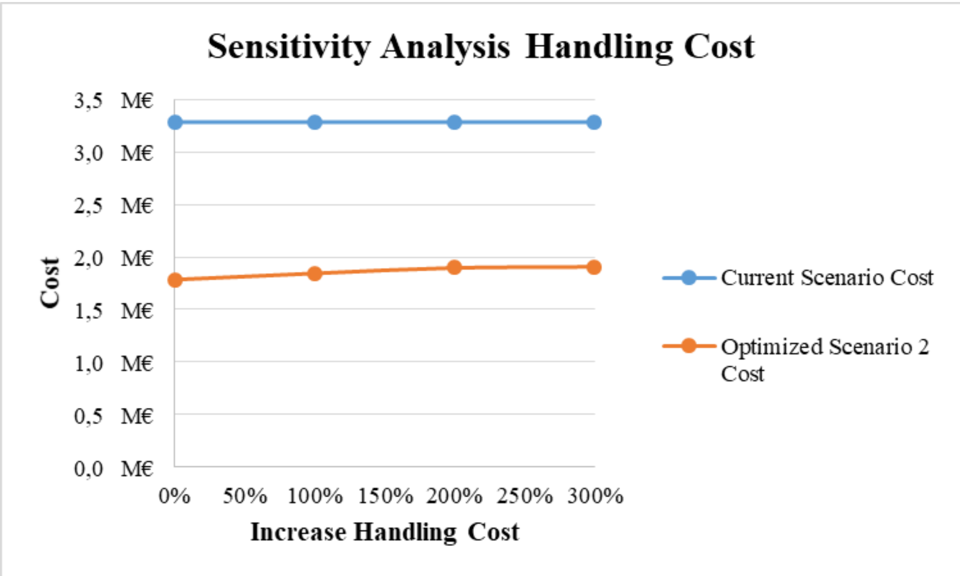

Figure 5.24. Current scenario and optimized scenario 2 cost – Handling cost sensitivity analysis

Regarding delivery frequencies, when handling costs are modified, only the delivery frequencies between the suppliers and the cross-docking facilities are impacted. In Figure 5.25 we present deliveries frequencies distribution per handling cost scenario, and in Figure 5.26 we show the total number of deliveries per year for each scenario as well. As expected, when handling cost is increased, delivery frequencies are reduced. Particularly when handling cost is multiplied by 4, delivery frequency decrease for 43% of the suppliers and the total number of deliveries per year for all the suppliers is reduced by 26%.

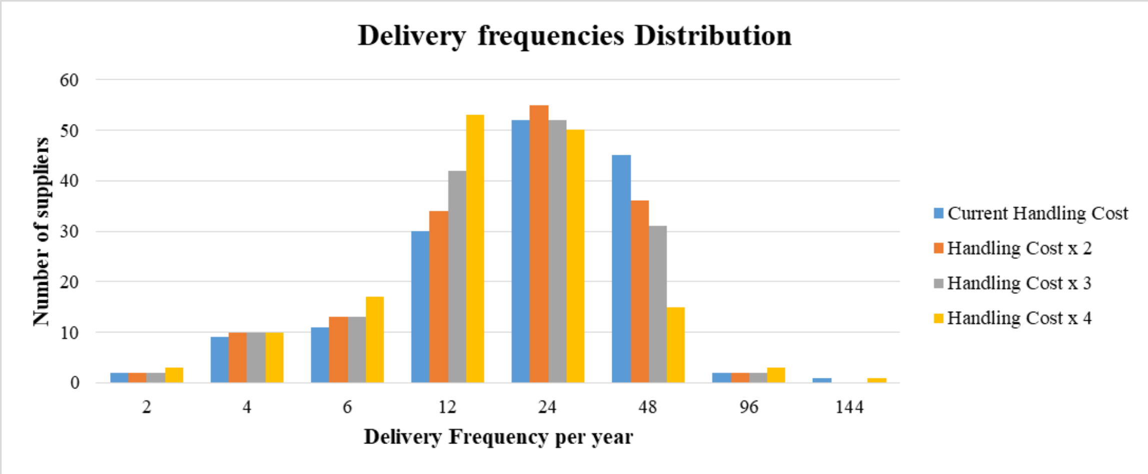

Figure 5.25. Delivery frequencies per year distribution per handling cost scenario

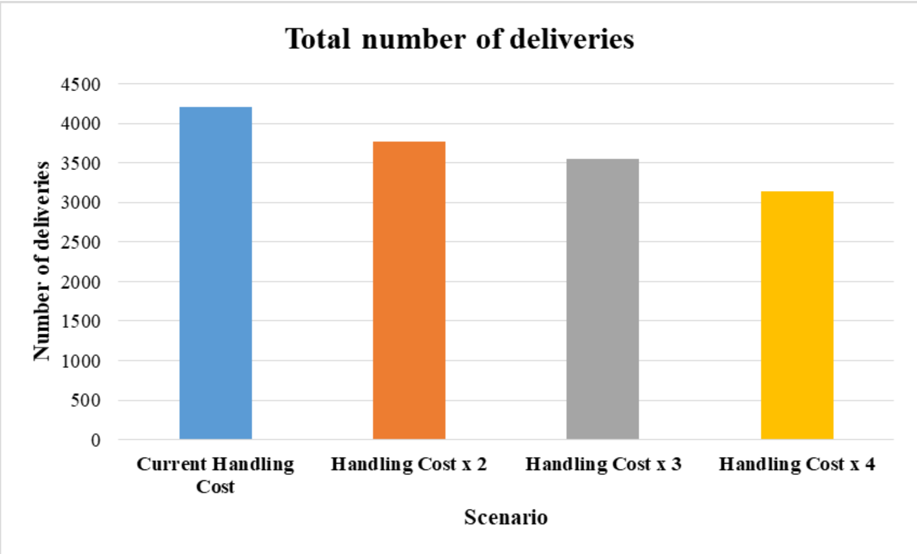

Figure 5.26. Total number of deliveries per year for all the suppliers per handling cost scenario

In conclusion, for big variations of the handling cost per pallet at the cross-docking facilities, total cost reduction achieved as well as total cost for the optimized scenario 2 do not vary significantly and the cross-docking facilities used are maintained. Only when it is multiplied by 4, the cross-docking facility at Toulouse is not used anymore. Regarding delivery frequencies, when handling cost is multiplied by 4, they are reduced for 43% of the suppliers.

5.3.6. Sensitivity Analysis Conclusion

In this section, we conduct a sensitivity analysis on transportation costs, storage cost and handling cost per pallet at the cross-docking facilities. When PCS and LTL costs increase, total cost reduction potential of reducing delivery frequencies increase due to big delivery frequencies and small shipment sizes in the current supply chain and inversely when PCS and LTL costs are reduced, total cost reduction achieved in the optimized scenario 2 is reduced. When FTL costs between the cross-docking facilities and Albacete are multiplied by two, no cross-docking facility is used. When PCS, LTL and FTL costs increase all (which may occur in reality), total cost reduction potential of reducing delivery frequencies increase and the same cross-docking facilities are used. Moreover, regarding delivery frequencies, as expected, when transportation costs increase, they are reduced, and when transportation costs are reduced, they increase.

Concerning storage cost, when it increases significantly, total cost reduction achieved in the optimized scenario 2 is reduced slightly and the same cross-docking facilities are used. In addition, delivery frequencies increase when it is reduced.

Finally, when handling cost increases significantly, total cost reduction achieved in the optimized scenario 2 is reduced slightly and the same cross-docking facilities are used. Only when it is multiplied by 4, the cross-docking facility at Toulouse is not used anymore. Regarding delivery frequencies, when handling cost increases, delivery frequencies are reduced. Table 5.30 presents a summary of the main sensitivity analysis results. In almost all the cases the same cross-docking facilities are used. Only for extreme values for the input costs they change. Hence the solution obtained is robust.

Cost	Cross-docking facilities used	Delivery frequencies (DF)	Cost reduction achieved (CR)
PCS and LTL transportation costs	They change only when PCS and LTL costs are multiplied by 7.	DF are reduced when PCS and LTL costs increase. Inversely they increase when PCS and LTL costs are reduced.	CR increases when PCS and LTL costs increase. It is reduced when they are reduced.
FTL transportation costs	If FTL costs are multiplied by two no cross-docking facility is used.	Not apply.	CR increases when FTL costs are reduced. It is reduced when they increase.
PCS , LTL and FTL transportation costs	Remain the same.	DF are reduced when PCS, LTL and FTL costs increase. Inversely they increase when PCS, LTL and FTL costs are reduced.	CR increases when PCS, LTL and FTL costs increase. It is reduced when they are reduced.
Storage Costs	Remain the same.	DF increase when storage costs increase.	When storage costs increase, CR is reduced slightly.
Handling Cost	The cross-docking facility at Toulouse is not used anymore when they are multiplied by 4.	DF are reduced when handling cost increases.	When handling cost increases, CR is reduced slightly.

Table 5.30. Sensitivity analysis summary

5.4. Conclusion

In this section, we combine the transportation lot sizing model, the transportation mode selection model and the cross-dock location model presented in chapters 3 and 4 in order to build a cost-efficient transportation solution for the AH case. **As a result, by optimizing transportation lot sizes, including sea freight in transportation mode alternatives for North America suppliers and using the two cross docking facilities at Toulouse and New York total cost and CO_2 emissions could be potentially reduced by 46% and 47% respectively (optimized scenario 2).** Regarding the milk run concept, it is shown that a milk run strategy around the cross-docking facilities is not profitable for AH due to small delivery volumes.

As it was mentioned in Section 2, the supply chain addressed is characterised by small production rates. As a consequence, manufacturers are in a position of weakness in relation to their suppliers given that they represent a small part of the turnover of their suppliers. This results in a constrained network configuration that is difficult to modify. Moreover in the supply chain addressed transportation is managed by suppliers and there is no visibility over transportation costs and operations. Table 5.31 shows the AH supply chain characteristics. Results obtained in this chapter show that inbound flow optimization and consolidation strategies as transportation lot sizing, transportation mode selection and cross-docking, can be considered in industries with similar characteristics in order to reduce costs. We highlight the fact that in order to implement these optimization strategies, it is necessary to modify transport management system in order to have control over transport operations. Furthermore, regarding the environmental dimension, as it was mentioned before, it is not included explicitly in models used in this chapter. However, by optimizing cost, CO_2 emissions are reduced by 47%. Hence cost optimization is also a first step towards a sustainable inbound supply chain.

AH Inbound Supply Chain Characteristics	
Transportation management	In 80% of the cases, suppliers manage transportation. There's no visibility over transportation operations.
Mean delivery frequency	In 63% of the cases, delivery frequency is bigger than or equal to once per week.
Mean shipment weight	In 86% of the cases, mean shipment weight is smaller than or equal to 70 kg.
Total volume delivered per year	Suppliers included in this study deliver 1750 tons per year.
Transportation modes	Three transportation modes are used: road freight, sea freight and air freight. Air freight is prioritized for oversea shipments. Road freight is the norm for continental shipments.
Delivery Methods	Three delivery methods are used: Parcel and Courier Services (PCS) for 90% of the shipments, Less than Truck Load (LTL) for 9.9% of the shipments and Full Truck Load (FTL) for 0.1% of the shipments.

Table 5.31. AH supply chain characteristics

Finally we conduct a sensitivity analysis on input costs. In almost all the cases the same cross-docking facilities are used. Only for extreme values for the input costs they change. Hence the solution obtained is robust. In the next chapter we integrate explicitly CO_2 emissions in our models in order to build a sustainable inbound supply chain solution. In the same way we will evaluate alternative green transportation modes and their potential benefits for our case.

6. How to Build a Sustainable Inbound Supply Chain Network

In the first five chapters, optimization models developed did not include CO_2 emissions explicitly. We developed them with the aim of minimizing total costs. CO_2 emissions were only measured at each stage for the results obtained. Results obtained in these chapters show that by reducing costs it is possible to reduce CO_2 emissions significantly. Thus, cost reduction is the first step towards a sustainable supply chain. In this chapter, we develop a new version of the cross-dock location model that includes explicitly CO_2 emissions, to see what happens in terms of cost if we want to go further in terms of CO_2 emissions reduction. We apply this model to the Airbus Helicopters (AH) case, including new transportation modes: rail freight and inland waterways freight. Afterwards, we conduct a case study on North America suppliers' relocation and we apply the new cross-dock location model developed to a new inbound supply chain network configuration with the North America suppliers relocated. Until this point, supply chain network was fixed, because of AH industrial constraints. However, one of the objectives of this chapter is to provide long-term strategies in order to reduce CO_2 emissions. For this reason, suppliers' relocation is studied in this chapter. Finally, we describe briefly, some alternative transportation modes as the electric road freight and cargo drones and their potential benefits for the AH case. Table 6.1 presents a summary of all the scenarios that will be evaluated in this chapter.

Scenario	Description
Optimized green scenario 1	The green cross-dock location model is applied to the AH instance in order to obtain the greenest possible solution. Rail-road and inland waterways-road delivery alternatives are included from the cross-docking facility at Paris to Albacete.
Suppliers relocation scenario 1	North American suppliers are relocated in Paris and Airbus Mexico in Poland. The cross-dock location model presented in chapter 5 is applied to this new network configuration.
Suppliers relocation scenario 2	North American suppliers are relocated in Paris and the sea destination port of Airbus Mexico is relocated in Tuxpan. The cross-dock location model presented in chapter 5 is applied to this new network configuration.
Optimized green scenario 2	North American suppliers are relocated in Paris and the sea destination port of Airbus Mexico is relocated in Tuxpan. The green cross-dock location model is applied to this network configuration in order to obtain the greenest possible solution. Rail-road and inland waterways-road delivery alternatives are included from the cross-docking facility at Paris to Albacete.

Table 6.1. Scenarios summary

6.1. Green Cross-Dock Location Model

We develop a modified version of the cross-dock location model presented in chapter 5. In this new version we limit the CO_2 emissions by defining a new constraint. We consider this approach is the most appropriate for our case as it allows to define the desired level of CO_2 emissions reduction based on a baseline scenario. Hereafter we present the new version of the model. New parameters and constraints are in green. As a reminder, suppliers have the option of delivering directly all the warehouses or passing through a cross-docking facility in order to deliver them. A supplier cannot deliver its products using both alternatives due to industrial constraints. Input costs and transportation modes for each alternative are defined using the transportation lot sizing model.

Sets

$N = \{1..i..n\}$: The set of suppliers.
$F = \{0..j..m\}$: The set of delivery alternatives for each supplier. For a supplier, 0 represents delivering all the warehouses directly and j represents delivering all the products for all the warehouses through the cross-docking facility j.
$M = \{1..j..m\} \subseteq F$: The set of potential cross-docking facilities.
$P = \{1..k..p\}$: The set of Warehouses.

Parameters

V_{ik}: Total volume (kg) delivered per year by supplier *i* to warehouse *k*.
K_{jk}: Capacity of the transportation mode used between the cross-docking facility *j* and the warehouse *k*.
f_j ($j \in \{1..m\}$): Fixed opening cost of the cross-docking facility j
${}'_{ij}$ ($j \in \{1..m\}$): Total cost per year of delivering all the products from supplier *i* using cross-docking facility *j* to all the warehouses. This cost includes transportation costs, handling costs, WIP cost (for sea freight shipments) and storage cost at the cross docking facilities and at the warehouse in function of FTL_{jk}.
C'_{i0}: Total cost per year of delivering products directly to all the warehouses from supplier *i*. This cost includes transportation cost, WIP cost (for sea freight shipments) and storage cost.
FTL_{jk} ($j \in \{1..m\}$): Fixed delivery frequency between the cross-docking facility *j* and the warehouse *k* (Times per year).
t'_{jk} ($j \in \{1..m\}$): Total fixed transportation cost per year of delivering warehouse *k* from the cross-docking facility *j* with a fixed delivery frequency FTL_{jk}.
E_{ij}($j \in \{1..m\}$): Total transportation CO_2 emissions per year if supplier *i* delivers all its products for all the warehouses through the cross-docking facility *j*. This parameter corresponds to emissions produced by transportation between the supplier *i* and the cross-docking *j*.
E_{i0}: Total CO_2 emissions per year if supplier *i* delivers all its products directly to all the warehouses. This parameter corresponds to emissions produced by transportation between the supplier *i* and the warehouses.
E'_{jk}($j \in \{1..m\}$): Total transportation CO_2 emissions per year if the cross-docking facility *j* delivers the warehouse *k*. This parameter corresponds to emissions produced by transportation between the cross-docking facility *j* and the warehouse *k*.
E_j($j \in \{1..m\}$): Total CO_2 emissions per year if the cross-docking facility *j* is used. This parameter corresponds to emissions produced by the energy used in the facility for cross-docking operations. The way in which these emissions are calculated is presented in Sections 4.1.5 and 5.2.4. Surface used at a crossdocking facility if it is used is fixed based on the hypothesis defined in these sections.
Z: Total CO_2 emissions per year limit
S_{jk}($j \in \{1..m\}$): Lower bound for volume delivered from the cross-docking facility *j* to the warehouse *k* in order to respect CO_2 emission factors constraints if the cross-docking facility *j* is used.

Decision variables

X_{i0}: Takes a value of 1 if supplier *i* delivers all its products directly to all the warehouses, 0 otherwise.

X_{ij} ($j \in \{1..m\}$): Takes a value of 1 if supplier *i* delivers all its products through the cross-docking facility *j* to all the warehouses and 0 otherwise.
X'_{jk} ($j \in \{1..m\}$): Takes a value of 1 if the cross-docking facility *j* delivers the warehouse *k*, 0 otherwise.
Y_j ($j \in \{1..m\}$): Takes a value of 1 if the cross-docking facility *j* is used, 0 otherwise.
q_{jk} ($j \in \{1..m\}$): Volume delivered from the cross-docking facility *j* to the warehouse *k*.

Model

$$\boldsymbol{Objective\ Function}: Min \sum_{i=1}^{n}\sum_{j=0}^{m} C'_{ij}X_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{p} t'_{jk}X'_{jk} + \sum_{j=1}^{m} f_j Y_j \quad (6.1)$$

Subject to

$$\sum_{j=0}^{m} X_{ij} = 1 \quad \forall i \in N \quad (6.2)$$

$$X_{ij} \leq Y_j \quad \forall i \in N, \forall j \in M \quad (6.3)$$

$$q_{jk} = \sum_{i=1}^{n} X_{ij} V_{ik} \quad \forall j \in M, \forall k \in P \quad (6.4)$$

$$q_{jk} \leq X'_{jk} FTL_{jk} K_{jk} \quad \forall j \in M, \forall k \in P \quad (6.5)$$

$$\sum_{i=1}^{n}\sum_{j=0}^{m} E_{ij}X_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{p} E'_{jk}X_{jk} + \sum_{j=1}^{m} E_j Y_j \leq Z \quad (6.6)$$

$$q_{jk} \geq X_{jk} S_{jk} \quad \forall j \in M, \forall k \in P \quad (6.7)$$

$$X_{ij} \in \{0,1\} \quad \forall i \in N, \forall j \in F \quad (6.8)$$

$$Y_j \in \{0,1\} \quad \forall j \in M \quad (6.9)$$

$$q_{jk} \in \mathbb{R}^+ \quad \forall j \in M, \forall k \in P \quad (6.10)$$

$$X_{jk} \in \{0,1\} \quad \forall j \in M, \forall k \in P \quad (6.11)$$

In this version of the cross-dock location model, we include new parameters for total CO_2 emissions per year for each one of the delivery alternatives: E_{ij}, E_{i0}, E'_{jk}. In the same way, we include total CO_2 emissions per year due to the use of the cross-docking facilities (E_j). Using these parameters, we define constraint (6.6), that ensures that the sum of the total transportation and cross-docking CO_2 emissions does not exceed the annual limit Z. In this way CO_2 footprint is included explicitly in the cross-dock location model.

CO_2 emissions factors defined for each transportation mode determine the CO_2 emissions input data for each one of the delivery alternatives (E_{ij}, E_{i0}, E'_{jk}). In the case of FTL road transportation between the cross-docking facilities and the warehouses, we use the emission factor defined in section 2.4.2. When using this emission factor we assume that the capacity use rate of the FTL road transportation mode is equal to or greater than 90% (for each truck used). In other words, we assume that the volume delivered to the cross-docking facilities is important enough to use 90% or more of the FTL transportation mode capacity. In order to ensure that this assumption is respected in the cross-dock location model, we include the parameter S_{jk} and the constraint (6.7). The parameter S_{jk} defines the lower bound for the volume delivered from a cross-docking facility j to a warehouse k in order to ensure that the capacity use rate of the transportation mode used between them respect the emission factors assumptions defined. Constraint (6.7) ensures the respect of this lower bound. We decide to fix S_{jk} given that ensuring a good capacity use rate of the transportation modes, reduce CO_2 emissions (the higher is the capacity use rate, the smaller is the emission factor) (McKinnon and Piecyk, 2011). In this case, we ensure that the capacity use rate for the FTL transportation mode is greater than or equal to 90%.

6.2. Green Inbound Supply Chain Solution 1

We apply the green cross-dock location model to the same AH instance defined in chapter 5 composed by 152 suppliers, 7 potential cross-docking facilities: London (England), Paris (France), Toulouse (France), Saint Etienne (France), Vitrolles (France), Zurich (Switzerland) and New York (United States) and one warehouse at Albacete.

In chapter five, we assume that a FTL road transportation mode is used from all the cross-docking facilities to Albacete, except the cross-docking facility at New York, from which a LTL sea transportation mode is used. In this chapter, we include two additional delivery alternatives: multimodal rail-road freight from the cross-docking facility at Paris to Albacete, and multimodal inland waterways-road freight from the cross-docking facility at Paris to Albacete. We include these transportation modes because they are less polluting than FTL road transportation and they are adapted to big delivery volumes obtained thanks to flow consolidation at the cross-docking facilities.

Concerning the rail-road delivery alternative, we assume that products are transported using rail freight from the cross-docking facility at Paris to the cross-docking facility at Vitrolles, and they are afterwards forwarded using FTL road freight from Vitrolles to Albacete (see Figure 6.1). Similarly, concerning the inland waterways – road delivery alternative, we assume that products are transported using inland waterways freight from Paris to Vitrolles, and they are after forwarded using FTL road freight from Vitrolles to Albacete (see Figure 6.2).

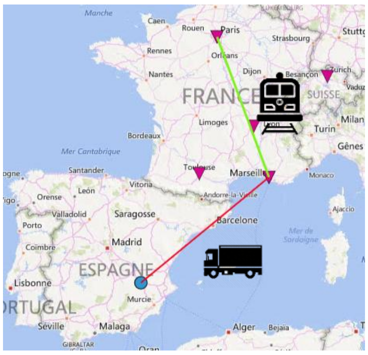

Figure 6.1. Rail-road delivery alternative

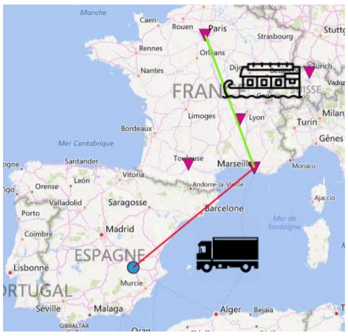

Figure 6.2. Inland waterways-road delivery alternative

Based on figures provided by DHL, we assume that rail-road multimodal transportation cost from Paris to Albacete is the same that road FTL transportation cost from Paris to Albacete defined for chapter 5. Concerning inland waterways- road transportation, we assume that inland waterways transportation cost is equal to 0.03 € per ton per km (Infomaniak network sa, 2020), and we use FTL road transportation cost defined in chapter 5 from Vitrolles to Albacete. Due to important inland waterways transportation delay (8 days [Fluviacarte, 2020]), we include WIP cost in total costs C'_{ij} for each supplier for this delivery alternative.

Regarding transportation CO_2 emissions: E_{ij}, E_{i0}, E'_{jk}, for road freight, sea freight and airfreight, they are estimated using the emission factors defined in Section 2.4.2. For inland waterways freight and rail freight we use the emission factors presented in Table 6.2. In order to estimate cross-docking CO_2 emissions, we maintain the assumptions defined in sections 4.1.5 and 5.2.4.

Mode	Emission Factor (gr CO2/ton.km)	Hypothesis
Rail freight	4	Emission factor retrieved from the ADEME website (Agence de l'Environnement et de la Maîtrise de l'Energie) for an average motorisation heavy cargo train (Bilans GES ADEME, 2019c)
Inland waterways freight	29	Emission factor retrieved from the ADEME website for a motorised barge from 400 to 649 deadweight tons (Bilans GES ADEME, 2019c)

Table 6.2. Rail and inland waterways emission factors

As in chapter 5, we run the cross-dock location model using Supply Chain Guru X. We run it for several values of the limit Z. We define these values based on total CO_2 emissions obtained for the optimized scenario 2 in Chapter 5: Total CO_2 emissions for the optimized scenario 2 are equal to 672 tons of CO_2 per year. Let us call this value B. We define different levels of reduction of B (99% of B, 98% of B, etc.) in order to generate the different values of Z. Results are presented in Table 6.3, Figures 6.3 and 6.4. We highlight the fact that CO_2 emissions reduction achieved compared to the optimized scenario 2 can be equal to or greater than the reduction imposed by the constraint 6.6.

Scenario	Cross-docking facilities used	Number of suppliers allocated	Volume Delivered per year (tons)	Total Cost	Tons of CO2 emitted per year	Cost Reduction compared to the current scenario	CO2 Reduction compared to the current scenario	Cost Increase compared to the Optimized Scenario 2	CO2 Reduction compared to the Optimized Scenario 2
Optimized Scenario 2	Toulouse	107	1152	1,78 M€	672	46,0%	47,3%	-	-
	New York	8	104						
Z = 99% *B	Toulouse	112	1089	1,79 M€	662	45,6%	48,2%	0,1%	1,6%
	New York	9	104						
Z = 98% *B	Toulouse	107	1152	1,79 M€	648	45,6%	49,2%	0,1%	3,6%
	New York	9	107						
Z = 97% *B	Toulouse	107	1152	1,79 M€	648	45,6%	49,2%	0,1%	3,6%
	New York	9	107						
Z = 96% *B	Toulouse	107	1152	1,79 M€	644	45,6%	49,6%	0,2%	4,3%
	New York	10	108						
Z = 95% *B	Toulouse	112	1089	1,79 M€	638	45,5%	50,1%	0,3%	5,2%
	New York	10	108						
Z = 94% *B	Toulouse	112	1089	1,79 M€	632	45,4%	50,5%	0,4%	6,0%
	New York	11	109						
Z = 93% *B	Toulouse	117	1095	1,8 M€	625	45,1%	51,0%	1,0%	7,0%
	New York	13	109						
Z = 92% *B	Toulouse	112	1089	1,81 M€	617	45,0%	51,7%	1,2%	8,2%
	New York	11	111						
Z = 91% *B	Toulouse	112	1089	1,81 M€	612	44,9%	52,1%	1,4%	9,1%
	New York	12	112						
Z = 90% *B	Toulouse	115	1092	1,82 M€	605	44,6%	52,6%	1,9%	10,0%
	New York	14	113						
Z = 89% *B	Paris (rail)	123	1057	1,9 M€	598	42,3%	53,1%	6,2%	11,0%
	New York	12	109						
Z = 88% *B	Paris (rail)	112	1089	1,9 M€	590	42,1%	53,8%	6,5%	12,2%
	New York	11	111						
Z = 87% *B	Paris (rail)	112	1089	1,9 M€	585	42,0%	54,2%	6,6%	13,0%
	New York	12	112						
Z = 86% *B	Paris (rail)	118	1053	1,91 M€	578	41,8%	54,7%	7,1%	14,0%
	New York	13	112						
Z = 85% *B	Paris (rail)	114	1057	1,92 M€	571	41,4%	55,2%	7,8%	15,0%
	New York	14	113						
Z = 84.2% *B (Greenest)	Paris (rail)	123	1037	1,95 M€	567	40,7%	55,6%	9,0%	15,8%
	New York	15	113						

Table 6.3. Green inbound supply chain solution 1 results

From Z = 99% of B (666 tons of CO_2 per year) to Z = 90% of B (605 tons per year), the solution obtained in the optimized scenario 2, does not change significantly. The same cross-docking facilities are used and cost reduction achieved compared to the current scenario decreases only by 1% when Z = 90% of B (it is reduced from 46% in the optimized scenario 2 to 44.6 % when Z = 90% of B). Total CO_2 emissions per year when Z = 90% of B are equal to 605 tons per year which corresponds to Z. CO_2 emissions reduction achieved in these scenarios is thanks to suppliers allocation. As it is shown in section 2.4.2, CO_2 emissions are estimated based on the volume delivered and the distance traveled. By increasing the number of suppliers allocated to a cross-docking facility, PCS and LTL distance traveled is reduced (the suppliers deliver the cross-docking facility instead of delivering Albacete). Similarly, when volume delivered to a cross-docking facility is increased, distance traveled by this volume using PCS and LTL road freight is reduced (this volume is delivered to the cross-docking facility instead of Albacete). At the cross-docking facility, shipments are consolidated and afterwards forwarded to Albacete using FTL road transportation or LTL sea transportation. FTL road freight and LTL sea freight emission factors are smaller than PCS and LTL road emissions factors, which explains CO_2 emission reduction. In some cases, suppliers allocated to a cross-docking facility increase while the volume delivered is reduced. In these cases, suppliers allocated are not the same. Moreover, CO_2 emission reduction achieved thanks to the increase of the number of suppliers allocated to the cross-docking facility is bigger than CO_2 emissions increase due to the reduction of the volume delivered to the cross-docking facilities.

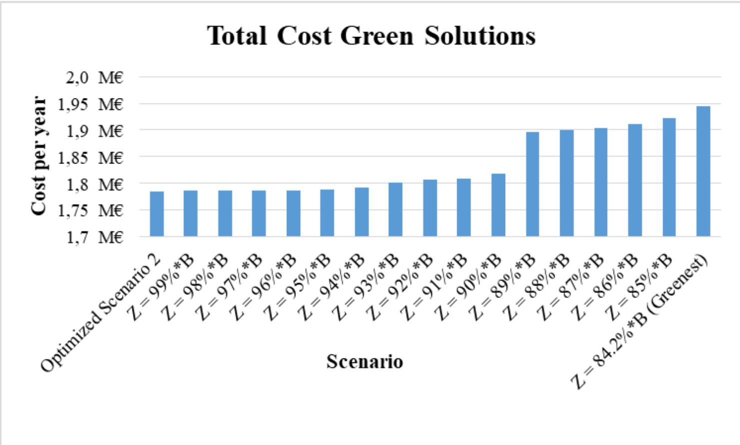

Figure 6.3. Total Cost Green Solutions

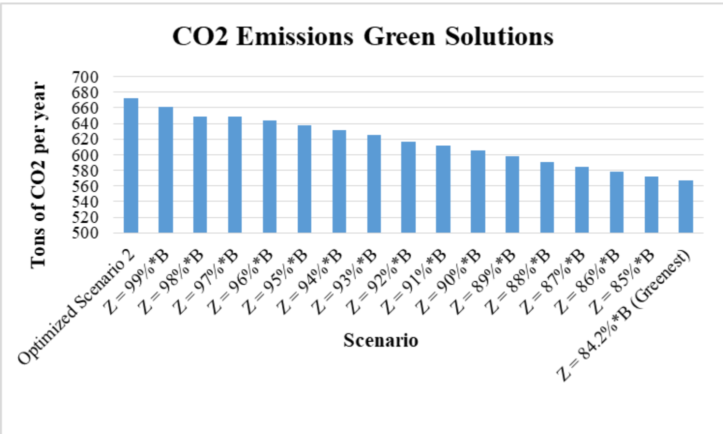

Figure 6.4. CO_2 Emissions Green Solutions

When Z is equal to 89% of B or lower, the cross-docking facility at Paris with multimodal rail-road transportation from there to Albacete is used instead of the cross-docking facility at Toulouse. This explains cost increase from Z =90% of B to Z = 89% of B and CO_2 emissions reduction thanks to the use of rail freight. From Z = 89% of B to Z = 84.2% of B, the same cross-docking facilities are used and CO_2 emissions reduction is achieved thanks to suppliers allocation. For values of Z lower than 84.2% of B there is no feasible solution. The inland-waterways-road freight alternative is never used because of important WIP costs. This means that the greenest possible solution with the delivery alternatives included in this study is achieved when Z = 84.2% of B. Let us call this scenario the optimized green scenario 1. Detailed costs and CO_2 emissions for this scenario compared to the optimized scenario 2 presented in Section 5.2.4 and the current scenario are presented in Tables 6.4 and 6.5 and in Figures 6.5 and 6.6.

Scenario	Cross-Docking Facilities used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks per year	Total Cost per year	% Cost Reduction
Current scenario		154 K€	99 K€	3,03 M€	0	3,3 M€	-
Optimized scenario 2	New York, Toulouse	451 K€	137 K€	1,13 M€	64 K€	1,78 M€	**46%**
Optimized green scenario 1	New York, Paris (rail)	512 K€	236 K€	1,13 M€	70 K€	1,95 M€	**41%**

Table 6.4. Total cost optimized green scenario 1

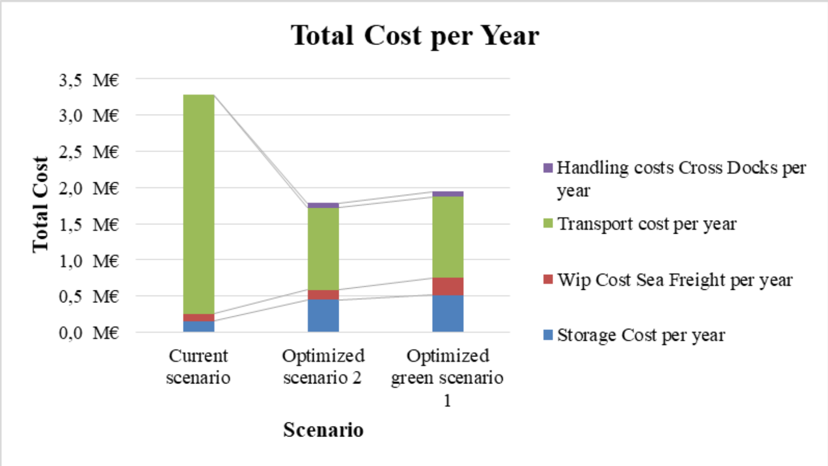

Figure 6.5. Total cost optimized green scenario 1

Tons of CO2 Emitted per Year			
Source	**Current scenario**	**Optimized scenario 2**	**Optimized green scenario 1**
Air	580	68	0
Road	688	582	538
Sea	10	21	23
Rail	0	0	3
Cross-Docking	0	2	2
Total	1277	672	567

Table 6.5. CO_2 emissions optimized green scenario 1

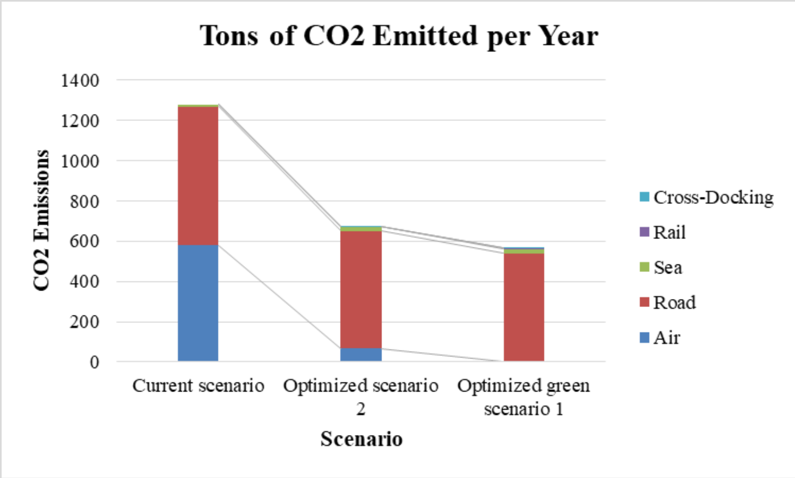

Figure 6.6. CO_2 emissions optimized green scenario 1

In the green optimized scenario 1, cost is increased by 9% and CO_2 emissions are reduced by 15.8% compared to the optimized scenario 2. As it was mentioned previously, this is mainly due to the fact that in the optimized green scenario 1, the cross-docking facility at Paris is used instead of the cross-docking facility at Toulouse, and multimodal rail-road freight is used from Paris to Albacete. In this scenario, 123 suppliers deliver 1036 tons to the cross-docking facility at Paris. Moreover, all the suppliers located in North America deliver the cross-docking facility at New York, hence air-freight is not used.

6.3. North America Suppliers Relocation

Until this point, supply chain network was fixed, because of AH industrial constraints. However, one of the objectives of this chapter is to provide long-term strategies in order to reduce CO_2 emissions. For this reason, in this section, we conduct a case study on North America suppliers relocation from an environmental point of view, even if solutions provided in this section may not be feasible in the short term.

Firstly, we study the relocation of Airbus Mexico in Poland and the rest of the North American suppliers in France. Then we evaluate another scenario where Airbus Mexico is not relocated, and the rest of North American suppliers are relocated in France. In this scenario, the destination seaport for Airbus Mexico is relocated. Finally, we apply the green cross-dock location model to this network configuration. These scenarios are defined assuming that production costs may be similar in one hand in Mexico and Poland and in another hand in France, United States and Canada.

6.3.1. Airbus Mexico in Poland and the Rest in France

The main reason for opening an Airbus site at Mexico was low labour costs. For that reason, in this section, we propose evaluating the relocation of this site in Poland, where we assume that labour costs are similar or slightly greater. For the rest of the North American suppliers, we evaluate their relocation in France. We assume that production costs would be similar in France, United States or Canada. Let us call this scenario the suppliers relocation scenario 1.

In order to define the location of the North American suppliers in France, we use existing suppliers' location in the Parisian region. Regarding Airbus Mexico, we suppose that the new location would be in Warsaw.

We run the cross-dock location model defined in Chapter 5 on this modified supply chain network configuration using Supply Chain Guru X. Results obtained compared to the optimized scenario 2 and the current scenario are presented in Tables 6.6 and 6.7 and in Figures 6.7 and 6.8.

Scenario	Cross-Docking Facilities used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks	Total Cost per year	% Cost Reduction
Current scenario	-	154 K€	99 K€	3,03 M€	0	3,3 M€	-
Optimized scenario 2	New York, Toulouse	451 K€	137 K€	1,13 M€	64 K€	1,78 M€	**-46%**
Suppliers relocation scenario 1	Toulouse	444 K€	-	1,03 M€	67 K€	1,54 M€	**-53%**

Table 6.6. Suppliers relocation scenario 1 cost

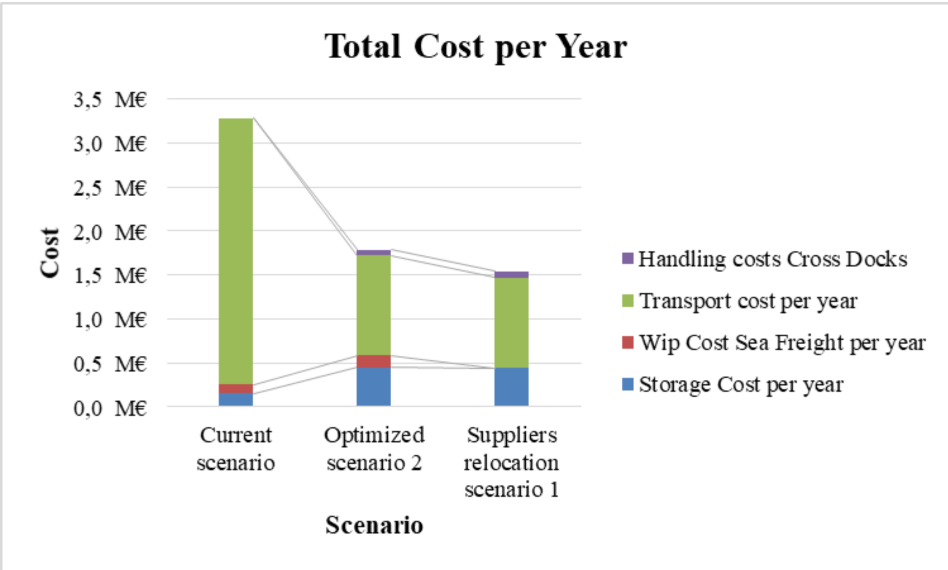

Figure 6.7. Suppliers relocation scenario 1 cost

Tons of CO2 Emitted per Year			
Source	**Current scenario**	**Optimized scenario 2**	**Suppliers relocation scenario 1**
Air	580	68	0
Road	688	582	540
Sea	10	21	0,1
Cross-Docking	0	2	1
Total	1277	672	541

Table 6.7. CO_2 emissions suppliers relocation scenario 1

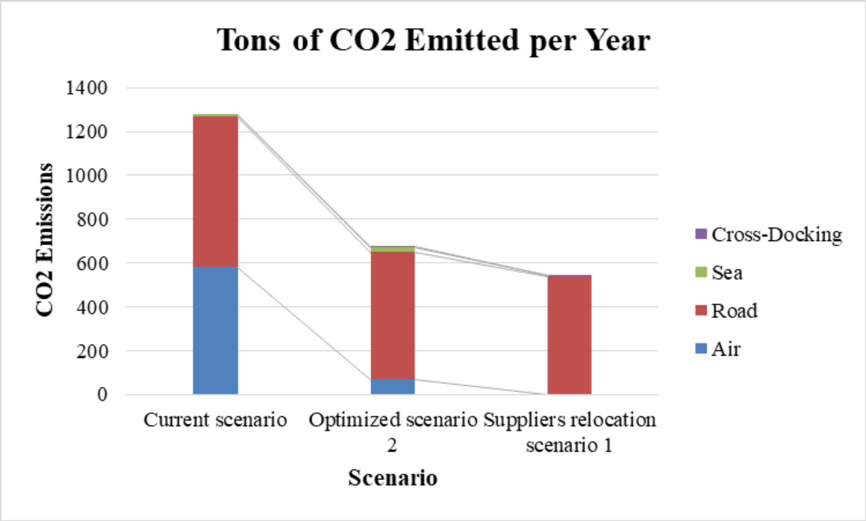

Figure 6.8. CO_2 emissions suppliers relocation scenario 1

As expected by relocating Airbus Mexico in Poland and the rest of the North American suppliers in France, total cost reduction achieved compared to the current scenario is increased from 46% in the optimized scenario 2 to 53% in the suppliers relocation scenario 1. Concerning CO_2 emissions they are reduced from 672 tons per year in the optimized scenario 2 to 541 tons per year. In one hand, there are no airfreight CO_2 emissions in the suppliers relocation scenario 1, and the only remaining sea freight CO_2 emissions are due to sea freight used from Morocco to Albacete. In the other hand, in the suppliers relocation scenario 1, road transportation from the American suppliers to the cross-docking facility at New York is removed, hence road transportation CO_2 emissions are reduced too (due to important distances traveled to New York). 126 suppliers deliver 119 tons per year to the cross-docking facility at Toulouse, including all the North American suppliers relocated. This explains also road CO_2 emissions reduction.

6.3.2. All in France except Airbus Mexico

In this section, we evaluate another scenario where the location of Airbus Mexico is not modified and the rest of North American suppliers are relocated in France in the same location than the previous section. However, this time, instead of delivering a port located in New York (Assumptions defined for the 5 previous chapters), Airbus Mexico delivers a port located in Tuxpan (Mexico), then parts are sent from Tuxpan to the port of Valencia as in chapter 5. We call this scenario the suppliers relocation scenario 2. Given that the Airbus Mexico site was opened recently, we evaluate this scenario in order to see if there is a way of achieving the same CO_2 emissions reduction level than in the suppliers relocation scenario 1, without relocating it.

We run the cross-dock location model defined in Chapter 5 on this modified supply chain network configuration using Supply Chain Guru X. Results obtained for this scenario compared to the optimized scenario 2, the current scenario and the suppliers relocation scenario 1 are presented in Tables 6.8 and 6.9 and in Figures 6.9 and 6.10.

Scenario	Cross-Docking Facilities used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks	Total Cost per year	% Cost Reduction
Current scenario	-	154 K€	99 K€	3,03 M€	-	3,3 M€	-
Optimized scenario 2	New York, Toulouse	451 K€	137 K€	1,13 M€	64 K€	1,78 M€	**-46%**
Suppliers relocation scenario 1	Toulouse	444 K€	-	1,03 M€	67 K€	1,54 M€	**-53%**
Suppliers relocation scenario 2	Toulouse	444 K€	118 K€	1,09 M€	67 K€	1,72 M€	**-48%**

Table 6.8. Suppliers relocation scenario 2 cost

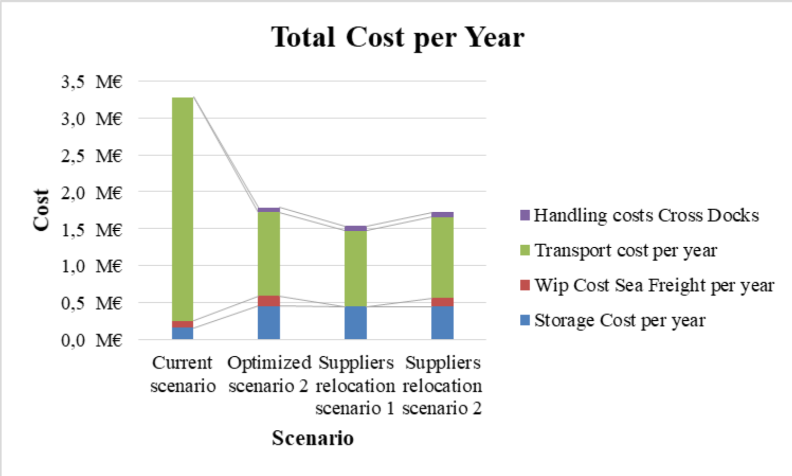

Figure 6.9. Suppliers relocation scenario 2 cost

Tons of CO2 Emitted per Year				
Source	**Current scenario**	**Optimized scenario 2**	**Suppliers relocation scenario 1**	**Suppliers relocation scenario 2**
Air	580	68	0	0
Road	688	582	540	489
Sea	10	21	0,1	25
Cross-Docking	0	2	1	1
Total	1277	672	541	516

Table 6.9. CO_2 emissions suppliers relocation scenario 2

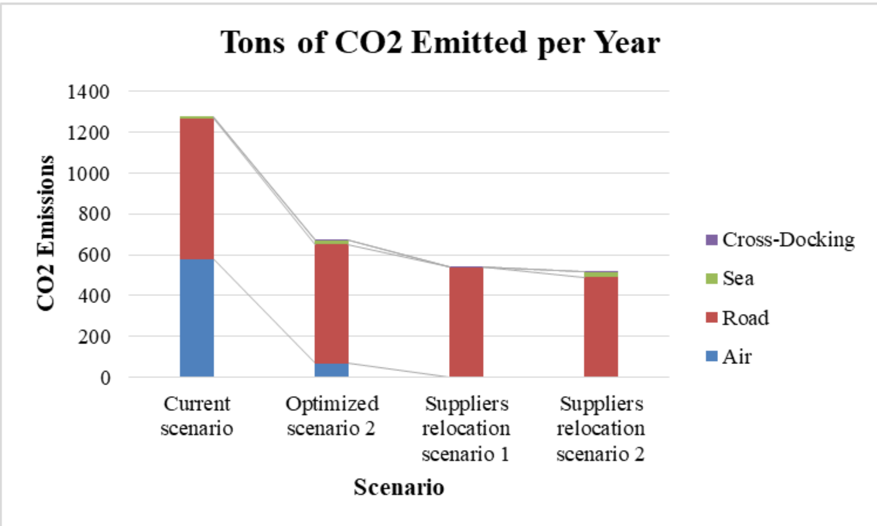

Figure 6.10. CO_2 emissions suppliers relocation scenario 2

Cost reduction achieved in the suppliers relocation scenario 2 increases from 46% to 48% compared to the optimized scenario 2. The suppliers relocation scenario 1 is cheaper than this scenario due to important WIP cost. Regarding CO_2 emissions, they are reduced from 541 tons per year in the suppliers relocation scenario 1 to 516 tons in the suppliers relocation scenario 2. As in the suppliers relocation scenario 1, there are no airfreight emissions thanks to supplier relocation. Road freight emissions are reduced too thanks to suppliers relocation and to the relocation of the destination port in the case of Airbus Mexico. By delivering the port of Tuxpan instead of delivering the port of New York, road distance traveled to deliver the port is reduced from 4122 km in the optimized scenario 2 to 434 km in the suppliers relocation scenario 2. In the same way, road distance traveled by shipments coming from Airbus Mexico in the suppliers relocation scenario 1 is reduced from 2872 km (distance traveled from Warsaw to Albacete) to 628 km (distance traveled from Airbus Mexico to the port of Tuxpan and from the port of Valencia to Albacete) in the suppliers relocation scenario 2. Finally, regarding sea freight emissions, they increase, compared to the optimized scenario 2 and the suppliers relocation scenario 1. In the suppliers relocation scenario 2, distance between the port of Tuxpan and the port of Valencia is 10651 km while in the optimized scenario 2, distance between the port of New York and the port of Valencia is 7079 km. However, sea freight CO_2 emissions increase is smaller than road freight CO_2 emissions reduction.

6.3.3. Z Limit and Suppliers Relocation

In the previous sections, we define the suppliers relocation scenario 1 and the suppliers relocation scenario 2. Suppliers relocation scenario 2 CO_2 emissions are smaller than suppliers relocation scenario 1 CO_2 emissions. For that reason, in this section we run the green cross-dock location model on the suppliers relocation scenario 2. As in section 6.2, we test different values for the limit Z, until we find the greenest possible solution with the North American suppliers relocated. Values of Z are defined in function of the total CO_2 emissions per year of the suppliers relocation scenario 2: Total CO_2 emissions for the suppliers relocation scenario 2 are equal to 516 tons of CO_2 per year. Let us call this value G. We define different levels of reduction of G (99% of G, 98% of G, etc.) in order to generate the different values of Z. Results are presented in Table 6.10 and Figures 6.11 and 6.12.

Scenario	Cross-docking facilities used	Number of suppliers allocated	Volume Delivered per year (tons)	Total Cost	Tons of CO2 emitted per year	Cost Reduction compared to the current scenario	CO2 Reduction compared to the current scenario	Cost Increase compared to the suppliers relocation scenario 2	CO2 Reduction compared to the suppliers relocation scenario 2
Suppliers Relocation Scenario 2	Toulouse	126	1119	1,72 M€	516	46,0%	59,6%	-	-
Z = 99% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 98% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 97% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 96% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 95% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 94% *G	Paris (rail)	125	1048	1,81 M€	483	45,0%	62,1%	4,8%	6,3%
Z = 93% *G	Paris (rail)	137	1041	1,81 M€	480	44,8%	62,4%	5,1%	7,0%
Z = 92% *G (Greenest)	Paris (rail)	134	1042	1,83 M€	475	44,3%	62,8%	6,2%	8,0%

Table 6.10. Z limit + Suppliers relocation results

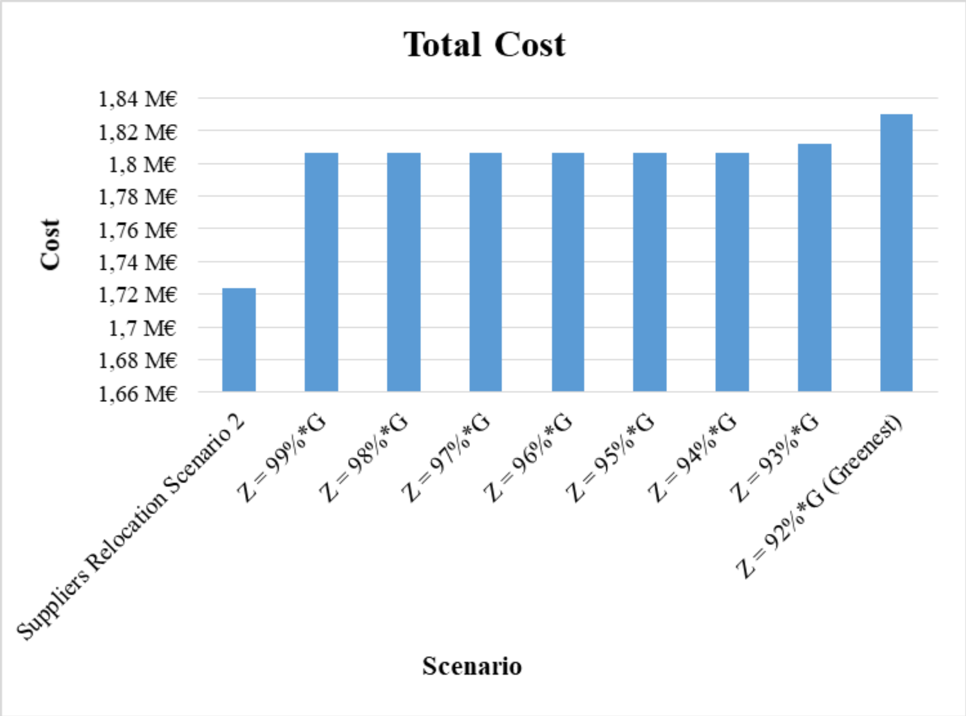

Figure 6.11. Z limit + Suppliers relocation results Cost

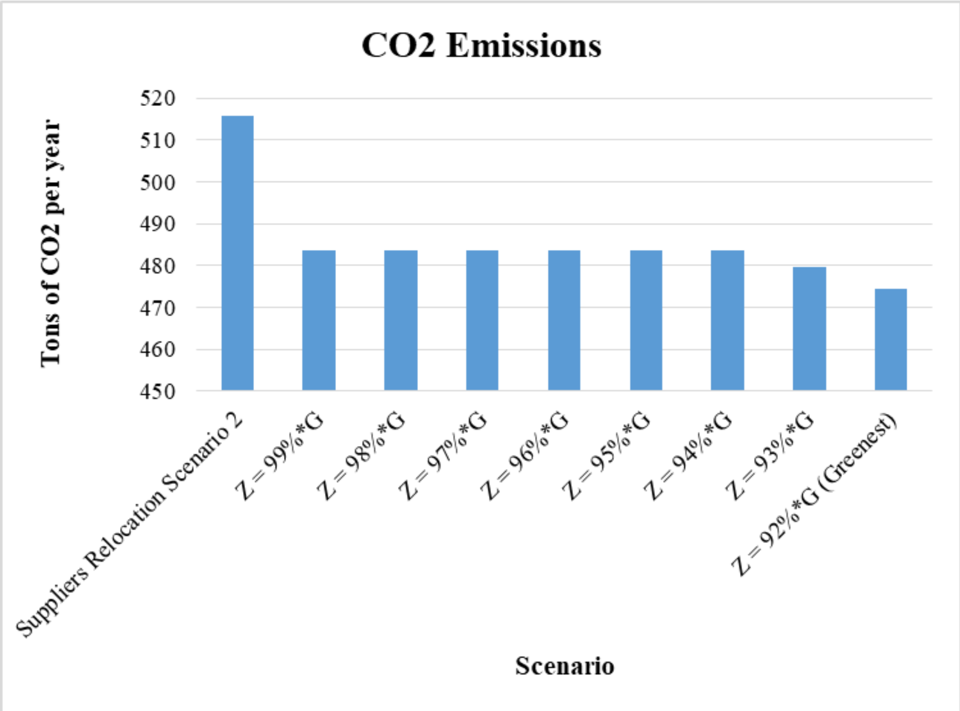

Figure 6.12. Z limit + Suppliers relocation CO_2 emissions

For levels of Z equals to or lower than 99% of G, the cross docking facility at Toulouse is not used anymore, instead of using it, the cross-docking facility at Paris is used. As in section 6.2, multimodal rail-road freight is used from Paris to Albacete. From Z = 99% of G to Z = 94% of G, the solution obtained is the same. CO_2 emissions reduction is achieved thanks to the use of multimodal rail-road freight between Paris and Albacete. For Z = 93% of G and Z = 92% of G, suppliers allocation to the cross-docking facility change. This explains supplementary CO_2 emissions reduction achieved. The greenest possible solution within the defined delivery constraints is obtained when Z = 92% of G. Let us call this scenario, the optimized green scenario 2. Detailed costs and CO_2 emissions for this scenario compared to the optimized scenario 2, the suppliers relocation scenario 2 and the current scenario are presented in Tables 6.11 and 6.12 and in Figures 6.13 and 6.14.

Scenario	Cross-Docking Facilities used	Storage Cost per year	Wip Cost Sea Freight per year	Transport cost per year	Handling costs Cross Docks	Total Cost per year	% Cost Reduction
Current scenario	-	154 K€	99 K€	3,03 M€	-	3,3 M€	-
Optimized scenario 2	New York, Toulouse	451 K€	137 K€	1,13 M€	64 K€	1,78 M€	**-46%**
Suppliers relocation scenario 2	Toulouse	444 K€	118 K€	1,09 M€	67 K€	1,72 M€	**-48%**
Optimized green scenario 2	Paris (Rail)	488 K€	118 K€	1,15 M€	70 K€	1,83 M€	**-44%**

Table 6.11. Optimized green scenario 2 cost

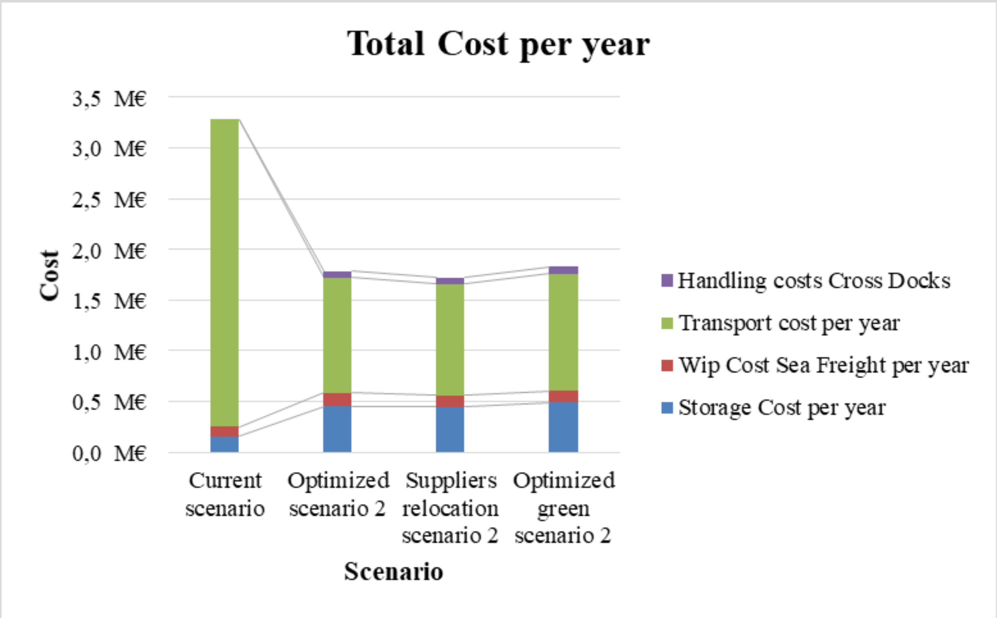

Figure 6.13. Optimized green scenario 2 cost

Tons of CO2 Emitted per Year				
Source	**Current scenario**	**Optimized scenario 2**	**Suppliers relocation scenario 2**	**Optimized green scenario 2**
Air	580	68	0	0
Road	688	582	489	445
Sea	10	21	25	25
Rail	0	0	0	3
Cross-Docking	0	2	1	1
Total	1277	672	516	475

Table 6.12. Optimized green scenario 2 CO_2 emissions

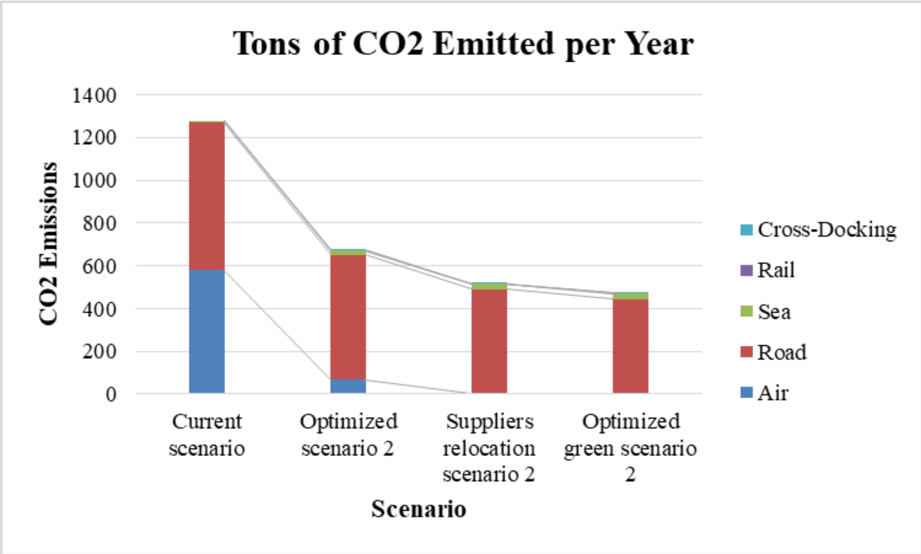

Figure 6.14. Optimized green scenario 2 CO_2 emissions

Compared to the optimized scenario 2, in the optimized green scenario 2, CO_2 emissions are reduced from 672 tons per year to 475 tons per year (29% reduction). This is thanks to suppliers' relocation, Airbus Mexico destination port relocation and the use of the cross-docking facility at Paris with multimodal railroad transportation from there to Albacete. In this scenario, total cost increases by 3% compared to the optimized scenario 2. Cost increase is negligible compared to CO_2 emissions reduction achieved.

Finally, in one hand, relocating suppliers is a cost efficient and a sustainable solution from a logistic point of view. In the other hand, suppliers' relocation strategies are very difficult to implement. It requires finding suppliers with the same production capabilities and with similar production costs which may be difficult due to the constraining product requirements in the aeronautic industry. However, supplier's relocation strategies are part of the recovery plan of the French government (Gouvernement, 2021). It stablishes support policies for suppliers' relocation strategies. Thus, this recovery plan could be an opportunity to implement suppliers' relocation strategies in the long term.

6.4. Electric Trucks and Parcel Delivery Drones

In this section, we describe briefly electric road transportation and delivery drones. We study electric trucks because the electric vehicles industry is growing and the electrification of the road transportation in the next years is imminent (IDTechEx, 2020). Regarding parcel delivery drones, we study them because it is a solution that is being developed by AH (Airbus, 2019) within the framework of a project called Skyways and it could perform better than road transportation for last-kilometer deliveries (Goodchild and Toy, 2017). Based on literature, we estimate the potential benefits of these solutions for the AH case. In the case of delivery drones, we conduct a case study on suppliers located near to the cross-docking facility at Paris for the optimized green scenario 1.

6.4.1. Electric Trucks

Currently, reducing CO_2 emissions for the transportation sector is becoming increasingly important. According to the International Energy Agency (IEA), transportation sector is responsible of 24% of direct CO_2 emissions due to fuel combustion. Road transportation accounts for three quarters of transportation CO_2 emissions. In this context, electric vehicles have emerged as an alternative in order to reduce transportation CO_2 emissions.

There are many articles that compare diesel road transportation and electric road transportation in terms of cost and environmental impact.

Lee *et al.* (2013) compare urban diesel delivery trucks and urban electric delivery trucks used for last kilometer deliveries. To this end, they estimate total cost of ownership (TCO) and life cycle energy use and greenhouse gases (CO_2 emissions) for both alternatives. In order to retrieve input data, they use a FedEx express parcel delivery truck and a 219 SEV Newton electric truck. Life cycle analysis includes vehicle operation, vehicle production and end-of-life management. Charging model for the electric truck is supposed to be a plug-in electric model. In other words, electric transportation requires charging stations infrastructure. The analysis is conducted for two drive cycles: the first one is characterized by a low average speed and frequent stops and the second one is characterized by a high average speed and less frequent stops. Results obtained show that for the first drive cycle electric trucks emits 42% to 61% less greenhouse gases (GHG) and consumes 32% to 54% less energy than diesel trucks. Similarly, the TCO for the electric truck in average is 22% smaller than the TCO for the diesel truck in this case. For the second drive cycle, results show that the electric truck emits 19 to 43% less GHG, and consumes 5% to 34% less energy. However, the TCO is 1% greater for the electric truck in this case.

Later Yang *et al.* (2018) conduct a study where they compare GHG emissions and TCO for light-duty and medium duty diesel trucks, plug-in electric trucks and battery-swap electric trucks. In their study, light-duty trucks group vehicles whose gross vehicle weight (GVW) is between 1800 kg and 6000 kg, and medium-duty vehicles group vehicles whose GVW is between 6000 kg and 14000 kg. Plug-in electric trucks refer to trucks using charging piles and charging stations. The main drawback of this way of charging is that trucks need to wait from 4 to 8 hours to be fully charged. Battery swap electric trucks refer to an alternative operating mode where there are battery rental companies who manage charging and distribution of batteries. In that way, each time that a battery is discharged, it is replaced by a battery rental company in 3 to 8 minutes. In order to estimate GHG emissions, Yang *et al.* (2018) use a simplified life cycle assessment (LCA) method. They include vehicle production, use, battery production and vehicle end-of-life in the LCA and in the TCO estimation. Results show in this case that for the light duty vehicles category, electric trucks emit on average 69% less GHG than diesel trucks. Inversely for medium duty vehicles it is shown that electric trucks emits on average 9.8% more GHG than diesel trucks. This is due mainly to the fact that medium heavy trucks requires bulky batteries which reduce the transportation capacity of the truck. Concerning the TCO, for light duty plug-in electric trucks, it is 37.8% lower than that of light-duty diesel trucks, and for light-duty battery swap trucks, it is 21% higher than that of light duty diesel trucks. For medium duty plug-in electric trucks, it is 6.7% lower than that of medium-duty diesel trucks, and for medium-duty battery swap trucks, it is 18.9% higher than that of medium duty diesel trucks.

Regarding heavy duty trucks, Çabukoglu *et al.* (2018) conduct a case study on the Swiss heavy duty fleet. Results obtained show that currently traditional electric trucks are unable to replace diesel trucks. Due to bulky and heavy batteries, it would be necessary to increase the maximum permissible transportation weight. Additionally, due to the range of batteries, heavy-duty electric trucks would not be able to travel the same distances than heavy-duty diesel trucks.

Hence, it would be necessary to increase the capacity of domestic charging grids and to implement battery-swapping infrastructures.

As it was shown, previously the battery electric medium duty and heavy duty trucks may not have a better performance than medium duty and heavy duty diesel trucks from an environmental point of view. **We highlight the fact that we assume that this is the current state of electric transportation. However, due to the rapidity with which technology is evolving in this area this assumption can be called into question in the short term**. An alternative for battery electric trucks are fuel-cell electric trucks. The main difference between these two technologies is that batteries store electricity, while fuel cell generates electricity using the chemical energy of a fuel, which is generally hydrogen. GHG reduction potential thanks to the use of hydrogen fuel cell depends on the way hydrogen is generated. It must be generated with renewable energy in order to reduce GHG emissions. Lao *et al.* (2020) conducted a case study in China in which they compare heavy duty diesel trucks and heavy duty fuel cell trucks. In their study, they use a GHG emission, pollutant emission and economic cost reduction in fuel cycle assessment model. In this case, they do not include vehicle construction and infrastructure construction and operation. They include only emissions related to fuel production and vehicle operation. They assume that hydrogen is generated using a seawater electrolysis process powered by offshore wind. Results obtained in this study show that by using fuel cell hydrogen trucks GHG emissions could be potentially reduced by 33%. In the last years, several advances have been done in the fuel cell heavy-duty trucks industry. As an example, Toyota and Hino Motors (Fuel Cells Bulletin, 2020a) decide to work together in order to develop a fuel cell vehicle for widespread use. The expected cruising range is 600 km which will be possible thanks to “a large capacity 700 bar hydrogen tank arrangement” that will allow meeting GHG emissions reductions requirements and commercial and economic requirements. Similarly Volvo and Daimler (Fuel Cells Bulletin, 2020b) signed recently a preliminary non-binding agreement in order to stablish a joint venture in order to develop fuel cell systems for heavy duty trucks that meet environmental and commercial requirements. As it was mentioned previously, one of the main challenges of fuel cell transportation is the production of hydrogen. Currently, Air Liquid (2021) is working on the development of low carbon technologies in order to produce hydrogen, for example using water electrolysis in conjunction with wind turbines or using proton exchange membrane (PEM) electrolyzer. Recently, Air Liquide finished the construction of the world largest PEM electrolyzer plant in Canada. This plant will contribute to the increasing demand of low carbon hydrogen in Canada.

Finally, in the current context, vehicle electrification is a solution for reducing GHG emissions. One of the major obstacles for companies to replace diesel trucks with electric trucks is high capital investment. However, in the next years GHG regulations will become increasingly constraining, which will increase diesel trucks costs. Similarly, with the growing fuel cell and battery production industry, electric vehicles will become cheaper thanks to economies of scale (IDTechEx, 2020).

In the Airbus case, in this study in order to estimate CO_2 emissions we use emission factors that take into account only fuel combustion. Hence, based on literature review, the electrification of the road fleet for Airbus would reduce significantly road CO_2 emissions (at least 30% reduction in the case of hydrogen fuel cells) caused by fuel combustion and would eliminate them in the case of battery electric light duty vehicles. Several transportation companies as DHL are taking part of this electrification process with the development of electric delivery vehicles solutions (DHL, 2019). If it is assumed that in the future electric road transportation would be as competitive as diesel transportation from an economic point of view, cost reduction achieved by solutions provided in this study would not be impacted.

6.4.2. Parcel Delivery Drones

In the last years, several companies start developing parcel delivery drones. As an example, currently Airbus is working on a project called Skyways (Airbus, 2019) in order to develop parcel delivery drones. The first units of these delivery drones are already working and are passing through a test phase. First trials took place at Singapore. This drone is able to carry at most 4 kg and travel as far as 3.5 km (7 km round trip distance). For its part, Amazon (Lardinois, 2019) also launched prime air, a project aiming to develop a new parcel delivery drone solution. Amazon's drone is able to carry at most 2.3 kg and travel as far as 12 km (24 km round trip distance). Delivery drones are an alternative transportation mode that may reduce CO_2 emissions for last-kilometer deliveries. Goodchild and Toy (2017) conducted a study in which they evaluate the CO_2 emissions reduction potential for parcel delivery drones compared to milk run road delivery. Results obtained show that drones are likely to perform better when destinations are close to the starting point and when there are a few recipients to deliver. Moreover, energy requirements for the drone have also an impact on the performance of the drone. For small energy requirements, drones perform better. Based on this article, we conduct a case study on the optimized green scenario 1 in order to evaluate drone delivery to the cross docking facility at Paris. To this end, we define the following assumptions. Concerning the drone, we assume that it is able to carry at most 2.3 kg, and travel as far as 12 km as the Amazon's drone. We do not use the Airbus drone data because distance range is not adequate for the Airbus case. There are 8 suppliers within a radius of 12 km from the cross-docking facility at Paris. For these suppliers, we compare transportation cost to the cross-docking facility at Paris, storage cost (at the cross docking facility and at Albacete), and CO_2 emissions between the defined road transportation solution in the optimized green scenario 1 and the parcel delivery drones solution.

In order to estimate transportation costs for delivery drones, based on the article of Wang (2016), we assume that cost per delivery is equal to 1€, which is an optimistic cost estimation that assumes that one operator is able to manage at least 5 drones and that a drone is able to make at least 30 deliveries per day. Regarding storage cost, we assume that shipment size for the drones delivery alternative is equal to 2.3 kg, and we estimate it for the cross-docking at Paris and Albacete using the equation (5.9) defined in Section 5.2.2. Concerning CO_2 emissions for drones we use the following formula based on the study conducted by Goodchild and Toy (2017):

$$\text{CO}_2 \text{ emissions (drones)} = D' * P' * EF' * K' \tag{6.3}$$

Where D' is the total distance traveled by the drone, P' is the average energy requirement per unit of distance in Wh per km, EF' is the emission factor per unit of energy (Wh) in France and K' is a factor in order to take into account the efficiency of the battery (power delivered to the drone divided by the power generated to charge the drone battery). We use the emission factor per Wh defined in Section 4.1.5 for cross-docking CO_2 emissions: 0.0571 Kg of CO_2 per kWh (Bilans GES ADEME, 2019b). Concerning K' we assume that battery efficiency is equal to 85% (average lithium-ion battery efficiency) (Valøen and Shoesmith, 2007).We estimate CO_2 emissions for drones for several values of P' based on the study conducted by Goodchild and Toy (2017). In their study, the most optimistic value for average energy requirement is 6.2 Wh per km, we use this value as the starting point and we increase it gradually until having a scenario where road transportation performs better than drones from an environmental point of view. Results are presented in Tables 6.13 and 6.14.

Scenario	Transport Cost	Storage Cost	Total Cost	% Diff
Optimized Green Scenario 1	13,1 K€	29 K€	42 K€	-
Drones Scenario	9,9 K€	47 K€	56 K€	35%

Table 6.13. Drone vs road transportation cost

Scenario	CO2 Emissions (Tons of CO2)	% Diff
Optimized Green Scenario 1	0,100	-
Drones Scenario -P' = 6.2 Wh/km	0,070	-30%
Drones Scenario -P' = 6.8 Wh/km	0,077	-23%
Drones Scenario -P' = 7.5 Wh/km	0,084	-16%
Drones Scenario -P' = 8.1 Wh/km	0,091	-9%
Drones Scenario -P' = 8.7 Wh/km	0,098	-2%
Drones Scenario -P' = 9.3 Wh/km	**0,105**	**5%**

Table 6.14. Drone vs road transportation cost CO_2 emissions

By using drones total cost increase by 35% compared to the road transportation. Cost increase is due to storage cost increase. Given that shipment size is 2.3 kg, for seven over eight suppliers delivery frequency increase and is bigger than delivery frequency between the cross-docking facility at Paris and Albacete (once per week). For these suppliers, parts must be stored at the cross-docking facility, which increases cost. Total number of deliveries per year increase from 250 in the optimized green scenario to 12033 in the drones scenario. Regarding CO_2 emissions, for P' equals to 6.2 Wh per km, drones solution allows reducing CO_2 emissions by 30%. Reduction achieved decrease when P' is increased. For values of P' greater than or equals to 9.3 Wh per km the road transportation solution performs better from a CO_2 point of view.

Taking into account results obtained, parcel drone delivery is not a cost-efficient solution for the Airbus case. Grouping orders and optimizing shipment sizes using road transportation is cheaper than implementing a drone delivery system. Regarding CO_2 emissions, even if in the most optimistic scenario CO_2 emissions are reduced by 30%, this reduction is not significant in the global scope due to the small number of suppliers within the distance range of the delivery drones. For the green optimized scenario 1 total CO_2 emissions per year are equal to 567 tons. By using the drones solution CO_2 emissions are reduced by 0.03 tons, which is only 0.005% of total emissions.

With the current drones capabilities in terms of distance range, the total CO_2 emissions reduction achieved by implementing drones delivery around the cross-dock facility at Paris is negligible. If distance range capabilities are increased, more suppliers would be able to use drones delivery, and CO_2 emissions reduction would be more important.

6.5. Conclusion

In this chapter, firstly, we integrate explicitly CO_2 emissions to the cross-dock location model. To this end, we define a limit Z in order to limit total CO_2 emissions. We apply this model to the Airbus case, including two new delivery alternatives: multimodal rail-road transportation and multimodal inland waterways-road transportation. Results obtained show that by using the cross-docking facility at Paris with multimodal rail-road transportation and the cross-docking facility at New York with multimodal sea-road transportation, CO_2 emissions could be reduced by 56% compared to the current scenario. This is called the optimized green scenario 1. Compared to the optimized scenario 2, where only cost is included explicitly in the optimization, CO_2 emissions are reduced by 16% and cost is increased by 9% in the optimized green scenario 1. Additionally, results obtained show also that it is possible to reduce CO_2 emissions by 10% with respect to the optimized scenario 2, by only modifying suppliers allocation to the cross-docking facilities used. This increases only by 1.9% total cost.

Secondly, we evaluate the relocation of the North American suppliers in Europe. We define two scenarios based on production costs constraints. In the first one, we evaluate the relocation of Airbus Mexico in Poland and the rest of the North American suppliers in France. We call this scenario the suppliers relocation scenario 1. With this modified network configuration, total cost reduction achieved compared to the current scenario is increased from 46% in the optimized scenario 2 to 53%. Concerning CO_2 emissions, they are reduced from 672 tons per year in the optimized scenario 2 to 541 tons per year. In the second scenario, we do not modify the location of Airbus Mexico. We only modify its destination seaport: it delivers a port located in Tuxpan (Mexico) instead of delivering the port in New York. The rest of North American suppliers are relocated in France as in the suppliers relocation scenario 1. We call this scenario, the suppliers relocation scenario 2. In the suppliers relocation scenario 2, cost reduction achieved increases from 46% to 48% compared to the optimized scenario 2. Regarding CO_2 emissions, they are reduced from 672 tons per year in the optimized scenario 2 to 516 tons per year in the suppliers relocation scenario 2. We apply the cross-dock location model with CO_2 emission constraints to the suppliers relocation scenario 2. We call this scenario the optimized green scenario 2. Results show that by delivering the cross-docking facility at Paris instead of the cross-docking facility at Toulouse and using multi-modal rail-road transportation from there to Albacete, total CO_2 emissions could be reduced from 516 tons per year to 475 tons per year. Suppliers relocation may not be feasible in the short term, however, assuming that production costs remain the same, it is proven to be a cost-efficient strategy that allows reducing CO_2 emissions significantly. Table 6.15 presents a summary of all the scenarios evaluated.

Scenario	Total Cost per year	% Cost reduction compared to the current scenario	Total CO2 emissions	% CO2 emissions reduction compared to the current scenario
Current scenario	3,3 M€	-	1277	-
Optimized scenario 2	1,78 M€	**46%**	672	**47%**
Optimized green scenario 1	1,95 M€	**41%**	567	**56%**
Suppliers relocation scenario 1	1,54 M€	**53%**	541	**58%**
Suppliers relocation scenario 2	1,72 M€	**48%**	516	**60%**
Optimized green scenario 2	1,83 M€	**44%**	475	**63%**

Table 6.15. Total Cost and CO_2 emissions summary

Afterwards, in this section we describe briefly electric road transportation and parcel delivery drones. Based on literature review, it is shown that currently battery electric light duty trucks, could perform better than diesel light duty trucks from an environmental and an economical point of view. Concerning medium-duty and heavy-duty trucks, hydrogen fuel cell electric trucks could be an alternative to reduce CO_2 emissions if hydrogen is produced using renewable energy. **We highlight the fact that we assume that this is the current state of electric transportation. However, due to the rapidity with which technology is evolving in this area**

this assumption can be called into question in the short term. In the next years GHG regulations will become increasingly constraining, which will increase diesel trucks costs. Hence, the industry of fuel cell and battery electric trucks will grow and electric vehicles will become cheaper thanks to economies of scale (IDTechEx, 2020). Similarly, the production of hydrogen from renewable energy will increase (Air Liquid, 2021) which will improve fuel cell electric vehicles performance. In this study, we estimate transportation CO_2 emissions due to fuel combustion for AH. The electrification of the road fleet for Airbus in the future would reduce significantly road CO_2 emissions (at least 30% reduction in the case of hydrogen fuel cells) caused by fuel combustion and would eliminate them in the case of battery electric light duty vehicles. Costs would not be impacted thanks to the development of the electric vehicles industry. Regarding parcel delivery drones, it is demonstrated that it is not a cost efficient solution for the AH case. From an environmental point of view, it may reduce CO_2 emissions by 0,005% per year. However, this reduction is not significant compared to the implementation effort required. This is due to the small number of suppliers within the distance range of the delivery drones.

Finally, results obtained show that by implementing a cross-docking strategy combined with multi-modal transportation, relocating suppliers and using electric transportation in the AH inbound supply chain or in general in supply chains similar to the AH supply chain (see Table 2.16 in Chapter 2) CO_2 emissions can be reduced significantly. Thus, from an environmental point of view, it is recommendable to implement a transport organization that allows controlling and optimizing transportation operations in the aeronautic industry.

7. General Conclusion and Perspectives

The aeronautic industry, and more particularly, the helicopters industry is characterized by small production rates (*i.e.* 30 helicopters per year for a type of helicopter) compared to others industries as the automotive industry for example. Due to small production volumes, helicopters manufacturers are often in a weak position in relation to their suppliers (they represent an insignificant part of the turnover of their suppliers). This results in a constraining supply chain network configuration. Furthermore, in several cases in the aeronautic industry, suppliers manage inbound transportation, and there is no visibility over transportation operations (Roy and Elias 2018). Taking into account these characteristics, the objective of this Ph.D. thesis was to develop optimization and modelling tools that support inbound Supply Chain Network Design (SCND) by minimizing total cost and reducing CO_2 emissions in the aeronautic industry and industries with the same characteristics.

Airbus Helicopters (AH) is a division of Airbus, a leader in the aeronautic industry. In the last years, the launching of a new range of helicopters at AH has been the occasion to innovate production and logistics systems. Particularly, inbound transportation process is going to be completely modified. Taking into account the Airbus transformation context and the objective of this study, we conducted a case study at AH. Firstly, we conducted an analysis of the current inbound supply chain of AH based on deliveries made in 2018 for a panel of 152 suppliers. Despite the fact that this is not a recent database, it represents well the current situation given that transportation organization has not been modified until now. Main findings show that the current inbound supply chain is not optimized as a whole; in 80% of cases suppliers manage transportation separately and there is no visibility over transportation operations. Furthermore, given that there is no visibility over transportation costs, currently, procurement policies are defined only in function of storage costs, which results in small shipment sizes and big delivery frequencies. Regarding transportation modes, only road freight, sea freight and airfreight are used, prioritizing airfreight for over sea shipments. Particularly, all the North American suppliers included in this study except Airbus Mexico, use only airfreight. Additionally, supplier's location suggested that the implementation of flow consolidation strategies is possible. The study conducted by Roy and Elias (2018) and some benchmarking analysis conducted by Airbus show that there are several companies in the aeronautic industry with a similar transportation management system. Hence, the optimization axes identified for the AH case can be applied to these companies too and in general, to companies with similar supply chains.

We identified four optimization axes after analyzing the AH current inbound supply chain: 1) transportation lot sizing, 2) transportation mode selection, 3) cross-dock location and 4) milk run concept. As it was mentioned in the introduction of this thesis, we propose a step-by-step approach in order optimize inbound SCND. With this approach, supply chain decision makers are able to analyze the implementation effort of each step compared to its benefit. In this way, we provide a very practical and affordable approach to transform. For his reason, for each one of the identified axes we developed an optimization model. These models were developed initially with the aim of minimizing total costs, without including CO_2 emissions explicitly. For transportation lot sizing, we developed a model based on the classic Economic Order Quantity (EOQ) model taking into account the AH transportation costs structure. We applied this model to the AH case, and results obtained show that by optimizing transportation lot sizes in function of storage costs and transportation costs, total costs and CO_2 emissions could be reduced by 40% and 24% respectively. Regarding transportation mode selection, we proposed a simple cost-based transportation mode selection model taking into account infrastructure constraints.

After applying this model to the AH case, it was found that by extending the use of sea freight as an alternative for all the North American suppliers, total costs and CO_2 emissions could be reduced by 2% and 23% respectively. Concerning the cross-dock location model, we developed a mixed integer linear programming (MILP) model based on the facility location problem (FLP). Using this model it was found that by implementing a cross-docking facility at Toulouse, total cost and CO_2 emissions could be potentially reduced by 16% and 13% respectively. Finally, for the milk run concept, we developed an activity based costing method in conjunction with a framework in order to evaluate potential benefits of its implementation. We conducted a case study for suppliers located in a radius of 80 kilometers around the cross-docking facility in Paris. As a result it is shown that compared to a direct delivery strategy, the milk run strategy including third party shipments could potentially reduce total cost by 50%. Conversely, implementing a milk run strategy including only the Airbus shipments would not be profitable for the company due to small delivery volumes. However, no conclusion about the profitability of the milk run concept for AH could be inferred with this study, because milk run concept needs to be studied in conjunction with cross-dock location.

After studying each one of the optimization axes separately, we combined them in order to develop a cost-efficient solution for AH using a step-by-step approach. The first step is to modify transportation organization in order to have visibility and control over transportation operations. Then, by optimizing transportation lot sizes, cost and CO_2 emissions could be reduced by 40% and 24% respectively. If, in addition, sea freight is included as an alternative for all the North American suppliers, cost and CO_2 emissions could be reduced by 41% and 33% respectively. Finally; **by optimizing transportation lot sizes, using a cross-docking facility at Toulouse, and using a cross-docking facility at New York with multimodal road sea freight from there to Albacete, total cost and CO_2 emissions could be potentially reduced by 46% and 47% respectively. We call this solution the optimized scenario 2.** Regarding the milk run strategy, it is shown that due to small delivery volumes and the small number of suppliers in the region of Toulouse, it is not a cost-efficient solution for AH. Even if this solution was obtained only by minimizing costs without including explicitly CO_2 emissions constraints, an important CO_2 emissions reduction (47%) is achieved thanks to consolidation strategies and the use of sea freight. Results obtained show that by optimizing transportation lot sizing and transportation mode selection, and by implementing cross-docking facilities, an important cost reduction could be achieved in the aeronautic industry.

In the last part of this study, we focused on the environmental dimension. To this end, firstly we integrate explicitly this dimension in our cross-dock location model defining a limit Z for total CO_2 emissions. We applied this new version of the cross-dock location model to the Airbus case too, integrating two new delivery alternatives to the model: multimodal rail-road freight and multimodal inland waterways-road freight**. Results show that compared to the scenario 2, by using the cross-docking facility at Paris with multimodal rail-road transportation from there to Albacete, and allocating all the North American suppliers to the cross-docking facility at New York, with multimodal sea road transportation from there to Albacete, CO_2 emissions could be reduced by 56% compared to the current scenario. Compared to the optimized scenario 2 CO_2 emissions are reduced by 16%. Regarding total cost, it increases by 9% compared to this optimized scenario 2.**

After including explicitly CO_2 emissions in our cross-dock location model, we conduct a study on North American suppliers relocation. We evaluate two scenarios defined taking into account production costs constraints. In the first one, we evaluate the relocation of Airbus Mexico in Poland and the rest of suppliers in North America. This is called the supplier relocation scenario

1. In this scenario, thanks to the new network configuration, cost is reduced by 53% when the cross-docking facility at Toulouse is used and transportation lot sizes are optimized and CO_2 emissions are reduced by 58%. In the second scenario, we do not modify the location of Airbus Mexico and the rest of suppliers are relocated in France as in the suppliers relocation scenario 1. In this scenario, Airbus Mexico delivers a seaport located in Tuxpan (Mexico) instead of delivering the seaport at New York. This is called the suppliers relocation scenario 2. With this new network configuration, by using the cross-docking facility at Toulouse total cost and CO_2 emissions are reduced by 48% and 60% respectively. We applied the cross-dock location model with the CO_2 emissions constraint to the suppliers relocation scenario 2. **It was found that with this modified network configuration by using the cross-docking facility at Paris with multimodal rail-road transportation from there to Albacete instead of the cross-docking facility at Toulouse, CO_2 emissions reduction could be increased to 63%. Cost reduction achieved is reduced to 44%. This is called the optimized green scenario 2.** Suppliers relocation may not be feasible in the short term, however it is proven to be a cost efficient strategy that allows reducing CO_2 emissions.

In order to evaluate the impact of the electrification of road transportation in the next years (IDTechEx, 2020) and to study the benefits of a solution that is currently being developed by AH, we described briefly electric road transportation and parcel delivery drones. Based on literature, it is shown that currently battery electric light duty trucks, could perform better than diesel light duty trucks from an environmental and an economic point of view. Concerning medium-duty and heavy-duty diesel trucks, hydrogen fuel cell electric trucks could be an alternative to reduce CO_2 emissions if hydrogen is produced using renewable energy. We highlight the fact that we assume that this is the current state of electric transportation. However, due to the rapidity with which technology is evolving in this area this assumption can be called into question in the short term. The electrification of the road fleet for Airbus in the future would reduce significantly road CO_2 emissions (at least 30% reduction in the case of hydrogen fuel cells) caused by fuel combustion and would eliminate them in the case of battery electric light duty vehicles. Costs would not be impacted thanks to the development of the electric vehicles industry in the next years (IDTechEx, 2020). Regarding parcel delivery drones it is demonstrated that it is not a cost efficient solution for the AH case. From an environmental point of view, it could reduce CO_2 emissions by 0,005% per year. However, this reduction is not significant (due to the small number of suppliers within the drone's delivery distance range: 12km) compared to the implementation effort required.

In the Chapter 6 we show that by using multimodal rail-road and sea-road transportation, relocating suppliers and using electric transportation, in addition to optimizing transportation lot sizes and transportation mode selection and implementing cross-docking facilities, CO_2 emissions could be significantly reduced (until 63% in the optimized green scenario 2) without increasing significantly logistics costs (the optimized green scenario 2 increases cost by 3% compared to the optimized scenario 2) in the aeronautic industry. As in chapter five, in order to implement these CO_2 emissions reduction strategies, it is necessary to have control over transportation operations.

Thanks to this study, we showed that it was necessary to modify the AH current transportation organization in order to have visibility and control over transportation operations. Thus, a project has been launched at AH in order to modify the current transportation organization. This is the first step towards an optimized inbound supply chain. As it was shown in the first part of this study, by optimizing cost, CO_2 emissions could be reduced in parallel. Hence, cost optimization will be also a step towards a sustainable inbound supply chain. In the next step, when GHG reduction requirements become more constraining, alternatives transportation modes as rail-road freight and electric road transportation could be implemented without impacting significantly total cost. Suppliers' relocation strategies could be implemented too.

As it was mentioned at the beginning of this chapter, the supply chain addressed in this study is characterized by small production rates. As a consequence, manufacturers are in a position of weakness in relation to their suppliers given that they represent a small part of the turnover of their suppliers. This results in a constrained network configuration that is difficult to modify. Moreover, in this supply chain transportation is managed by suppliers, which results in an inbound supply chain that is not optimized as a whole. Despite these facts, results obtained show that by implementing flow consolidation and optimization strategies as transportation lot sizing, transportation mode selection and cross-dock location, important cost reduction and CO_2 emissions reduction could be achieved in this supply chain. The implementation of these consolidation strategies requires modifying the transportation management system in order to have control and visibility over transportation operations. Results obtained demonstrate the potential benefits of modifying the transportation management system.

Finally, due to the complexity of data recollection process, this study was limited to a panel of 152 suppliers. It is recommendable to conduct a study including all the AH suppliers. This may increase cost reduction and CO_2 emissions reduction potential of the solutions proposed and enhance the possibility of implementing other optimization strategies as the milk run concept. This study includes only inbound transportation (transportation between the suppliers and the production sites). The inclusion of inter-site transportation (transportation between the production sites) and outbound transportation (transportation to the customers) may also increase the benefits achieved and enhance the implementation of new optimization strategies. In the same way, this study could be extended in order to integrate the Airbus flow with flow of other companies. This could enhance the possibility of studying other optimization axes as well, for example logistics pooling (Pan *et al.*, 2013). We can go further on this approach and evaluate the possibility of implementing an open, decentralized and intelligent logistics system where decision making process takes place thanks to real time data analysis and the use of new technologies (*i.e.* Internet of Things, self-driving vehicles etc.) (Pan, 2017). Regarding alternative transportation modes as the delivery drones, another study could be conducted in which technology capabilities are improved (*i.e.* the distance range is increased). This could increase the optimization potential of these solutions. Concerning the models developed, in this study, we integrate the lean dimension by minimizing total cost and the sustainability dimension using CO_2 emissions constraints. These models can be modified in order to include carbon taxes, integrate the sustainability dimension by defining a multi-objective function or include the whole life cycle assessment of the supply chain addressed. Furthermore, we take into account only the lean and the sustainable dimension. Models could be extended in order to integrate other dimensions as the agile dimension in order to optimize customer service level by including lead times. Finally concerning the research framework, the models developed are proposed as modelling and decision tools used to support decision making process in inbound SCND. We propose a step-by-step approach in order optimize inbound SCND as we want to evaluate clearly the benefit of each step for the type of industry addressed in order to provide a very practical and affordable approach to transform. However, the research framework proposed could be extended in order to evaluate an integrative approach too.

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9. Annexes

A.1. Airbus Helicopters

Airbus Helicopters (AH) is a division of Airbus, a worldwide leader in the aerospace industry. With approximately 22000 employees all around the world, AH is the first helicopter manufacturer, with a turnover of 6 billion of euros in 2020. Its actual fleet is composed of 12000 helicopters operated by more than 3000 customers in approximately 150 countries.

Airbus Helicopters (AH) is the result of several fusions and acquisitions where the main stages are presented as follows:

- ***1992***: Creation of Eurocopter as the result of a fusion between two companies :
  - **Aérospatiale**: French Company, first general European aeronautic constructor and exporter
  - **Deutsche Aerospace AG (DASA)**: German company, important airplanes constructor during the Second World War.
- ***2000***: Eurocopter integration in the EADS group (European Aeronautic Defense and Space). The EADS was created by France, Spain and the groups Largadère and Daimler. It was the result of the fusion of almost all the constructors of these countries.
- ***2014***: The group EADS takes the name of his leading brand, Airbus, and becomes Airbus group. Eurocopter is named Airbus Helicopters.
- ***2017***: There is a fusion between the aviation commercial branch Airbus SAS and Airbus Group SAS. This new fusion is named Airbus.

Products

Airbus Helicopters has two ranges of helicopters: the civil range and the military range. One helicopter can be produced in different versions according to the type of mission that it must accomplish: Emergency Medical Services **(EMS)**, Search and Rescue operations **(SAR),** Professional or Private travel **(CIP)**, **Offshore Transport**, **Aerial Work** and **Security Services**.

A.2 Total Cost and CO_2 Footprint Comparison Before and After the Logistics 4.0 Project

In this section, we estimate total transportation cost and CO_2 emissions for the current supply chain (before transferring the stock to Albacete) and the logistics 4.0 supply chain (after transferring the stock to Albacete) for the perimeter of this thesis. In this analysis we include **Safran Helicopters**.

A.2.1 Total Cost

We estimate total transportation cost, storage cost, WIP cost, surface cost and labour cost for the current and the logistics 4.0 supply chain. In order to estimate transportation cost, storage cost and WIP cost we use the same hypothesis defined in Chapter 2.

In order to estimate surface costs and labour (handling and storage operations) costs we use the total logistics costs repartition for 2018 shown in Table A.1. In this Table, there is a repartition between external costs and internal costs. External costs refer to outsourced logistics and internal refers to logistic managed by AH. Transportation cost do not include inbound transportation costs (they are included in parts costs). Based on surface cost per square meter and working unit costs for Marignane, Donauworth and Albacete we calculate surface and labour cost reductions achieved with the logistics 4.0 project (Table A.2 and Table A.3).

Logitics global costs repartition 2018	
Part	**%**
Labour cost - external	69%
Labour cost - internal	6%
Transportation Cost	5%
Surfaces total cost - internal	11%
Surfaces total cost - external	9%
TOTAL	**100%**

Table A.1. Logistics costs repartition 2018

Surface costs		
Location	**Cost €/m2**	**% reduction**
Marignane and Donauworth	100	-
Albacete	27	73%

Table A.2. Surface costs (normalized because of AH privacy policies)

Working unit total cost - external		
Location	**K€ /year**	**% reduction**
Marignane and Donauworth	100	-
Abacete	79	21%

Table A.3. Working unit costs (normalized because of AH privacy policies)

Using the 2018 logistics cost repartition and the cost reductions defined in Tables A.2 and A.3, we estimate global labour costs and surface costs for the current supply chain and the logistics 4.0 supply chain. Finally using turnover repartition between the suppliers included in the perimeter of the study and all the suppliers, we estimate surface and labour costs for the perimeter of the study by prorating global surface and labor costs based on the turnover (Table A.4 and Table A.5).

Surface Costs per Year	
Scenario	**Cost €/ year for the perimeter of the study**
Current supply chain network	2,24 M€
Logistics 4.0 supply chain network	610 K€

Table A.4. Surface cost per year estimation

Labour Costs per Year	
Scenario	**Cost €/ year for the perimeter of the study**
Current supply chain network	7,62 M€
Logistics 4.0 supply chain network	6,03 M€

Table A.5. Labour cost per year estimation

Transportation Cost, Storage Cost and WIP Cost are estimated based on the database containing deliveries for 2018 mentioned previously. It is assumed that each shipment is delivered using the minimum cost delivery method, respecting transportation mode constraints. Resulting total cost repartition for 2018 is presented in Table A.6. We can see that with logistics 4.0 project total cost is reduced by 18% (2.2M€) compared to the current supply chain. Even if transportation cost increases from 1.93 M€ to 3.07 M€ due to transportation distance increase and extra transportation between Albacete and Marignane, and Albacete and Donauworth, this increase is largely offset by the surface and labour cost reduction. Additionally, labour costs account for more than 60% of the total cost for both scenarios.

Finally, from an economical point of view, results obtained with this analysis validate the AH decision to transfer stock to Albacete.

Scenario	Storage Cost per year	Transport Cost per year	WIP Cost Sea Freight per year	Subtotal Cost per year	Surface Cost per year	Labour Cost per year	Total Cost per year	% Cost Reduction
Current supply chain network	273 K€	1,93 M€	99 K€	**2,3 M€**	2,24 M€	7,62 M€	**12,2 M€**	-
Logistics 4.0 supply chain network	193 K€	3,07 M€	99 K€	**3,4 M€**	610 K€	6,03 M€	**10,0 M€**	**-18%**

Table A.6. Current vs Logistics 4.0 supply chain total cost per year

A.2.3 Transportation CO_2 Footprint

In order to estimate transportation CO_2 emissions we use the hypothesis defined in Chapter 2. Tons of CO_2 emitted as well as total weight delivered per transportation mode are presented in Table A.7 and Table A.8 for the current and the logistics 4.0 supply chain. As for total cost analysis, CO_2 analysis is conducted based on the file containing deliveries for 2018. In this case, we assume that if there is a shipment coming from Mexico delivered using sea freight to Donauworth and another shipment delivered using airfreight to Marignane the same day in this file, both are delivered using sea freight in the logistics 4.0 scenario to Albacete. For that reason, tons delivered using sea freight as well as sea freight CO_2 emissions increase in the logistics 4.0 supply chain, while tons delivered using airfreight and airfreight CO_2 emissions are reduced.

Even if there is a reduction of CO_2 emissions for airfreight in the logistics 4.0 scenario thanks to airfreight and sea freight shipments grouping, total CO_2 emissions increase by 21% from 1070 tons to 1293 tons compared to the current supply chain. This is due to transportation distance increase and extra FTL transportation between Albacete and Marignane, and Albacete and Donauworth.

Finally, results show the decision of transferring all the stock to Albacete is not on line with the sustainability dimension of this project. Hence, one of the objectives of this project was to identify different guidelines in order to minimize CO_2 emission and integrate the environmental thinking in the logistics 4.0 supply chain.

Current Supply Chain Transportation Carbon Emissions				
Transport Mode	**Tons delivered (2018)**	**% Weight**	**Tons CO2 emitted (2018)**	**% CO2**
Air	83	5%	770	**72%**
Road	1687	93%	292	**27%**
Sea	35	2%	9	**1%**
Total	**1805**	**100%**	**1070**	**100%**

Table A.7. Current Supply Chain CO_2 emissions 2018 – inbound transportation

Logistics 4.0 Supply Chain Transportation Carbon Emissions				
Transport Mode	**Tons delivered (2018)**	**% Weight**	**Tons CO2 emitted (2018)**	**% CO2**
Air	65	4%	580	45%
Road	1687	93%	703	54%
Sea	53	3%	10	1%
Total	**1805**	**100%**	**1293**	**100%**

Table A.8. Logistics 4.0 Supply Chain CO_2 emissions based on 2018 data – inbound transportation