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

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Abstract
Use of composites in aerospace has been increasing regardless of prohibitive costs of material, development and manufacturing. In an industry defined by global, complex networks of partners-suppliers that work symbiotically to develop high-value long-lasting products, every single improvement is critical. Growing air traffic and increasing backlogs suggest higher pressures on the industry and supply chains, demanding additional coordination effort of these networks.
In this research, a Mixed-Integer Programming model is proposed to aid on decisions of global network supply chain design for Carbon Fibre-Reinforced Polymer manufacturing in aerospace industries. In general, the model considers a (1) superstructure of entities and locations, a (2) transportation network, the (3) distance between all entities/locations, a (4) set of resources, materials, technologies and time constraints, and respective manufacturing needs, (5) a set of alternative processes, and the (6) economic, social and environmental impacts of all of decisions. This model is based on sustainable performance measures, thus aiming at maximising economic return, and minimising environmental and social impacts. The case of Embraer is presented and four forming processes are compared.
Among other conclusions, further study is recommended for the adoption of VBO as a promising technology that meets economic performance standards comparable to those of TA and factors like batch size, scale-up, demand and part length have great impact on this recommendation.

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

Contents:

1 Introduction

The airline industry as is known today owes much to the Convention on International Civil Aviation (held in Chicago in 1944), which outlined the international rules for aviation that aimed to increase safety and security. These rules shaped airline operations, both international and domestic, paving the way for the first set of global standards of the industry. The tragic events of September 11, 2001, have also changed the industry of air transportation, resulting in increased security procedures to ensure the safety of passengers and cargo (Febeliano, 2008). From 1944 on, the airline industry has undergone many changes, especially in what concerns business models. Throughout the '60s, air travel was a remarkable event and object of desire for most of the middle class. These traditional network carrier (or full-service network carrier (FSNC)) business models were challenged by the low-cost carrier (LCC) business models, more focused on serving the simple, short-haul passenger demand. Nowadays, aviation and related activities are a driver for growth and skilled employment. The figures speak for themselves: a total of 900 airlines worldwide, a combined fleet of nearly 22,000 aircraft serving around 1,670 airports, managed by approximately 160 air navigation service providers yield an overview of the impact of air transport (European Commission, 2011). As of 2005, the air transport industry generates 13.5 million jobs - of which 5 million are direct jobs -, without mentioning other activities supported by air travel (e.g., tourism). In Europe alone, air transport can generate 4.5 million jobs, adding 220 billion € to Gross Domestic Product (GDP). European integration and cohesion are also strongly affected by air travel (European Commission, 2011).

The primary goal of this paper is to help closing the identified research gap for sustainable Supply Chain (SC) optimisation models designed for the aerospace industry that account for the introduction of new materials. The research question linked to this is to find out which manufacturing process should be adopted by the industry for composite Carbon Fibre-Reinforced Polymer (CFRP) parts, based on sustainable performance measures. Aligned with Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries (IAMAT) on the pursuit of a framework to evaluate and decide on the appropriate process, only four forming processes are considered: (1) Traditional Autoclaving (TA), (2) Vacuum-Assisted Resin Infusion (VARI), (3) Vacuum-Bag Only (VBO) and (4) Thermo-Stamping (TS). The research objectives include getting acquainted with the aerospace industry and Supply Chain (SC), acquire deeper understanding of advanced materials, contribute to the academic community in the proposed field, help solving the problem identified and develop the skillset and awareness typical of research projects. For this, a Mixed-Integer Programming (MIP) model is proposed for aiding on decisions of global network SC design for CFRP manufacturing in aerospace industries, aiming at maximising economic return, and minimising environmental and social impacts. The methodology followed for this work is depicted in Fig. 1.

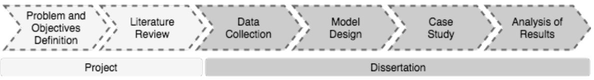

Figure 1: Steps of the research methodology.

2 Case Study and Model Development

In this section, the problem studied is framed and a Mixed-Integer Programming (MIP) model is proposed for aiding on decisions of global network SC design for CFRP manufacturing in aerospace industries. A model framework is also presented ahead, along with a description of each model objective.

The testbed model being used is formed by the set of stringer and skin, with 500mm long and 150mm wide. This testbed is considered to be representative and a building block of most complex aerostructures (e.g., wings, fuselage, or flaps). Even though the testbed exhibits a "T" transversal profile, only the base skin is considered on this research to enable the comparison and validation with the work of Santos (2017) and Marques (2018). The reference aerostructure being considered ahead for the case study follows a series of scale-up principles and relations introduced by Marques (2018).

Ideally, the SC network design includes multiple suppliers with different characteristics, several locations for installing facilities and a variety of transportation modes, enabling the model to select the optimal conditions. A graphical representation of the SC network structure considered for the problem and respective flows is shown in Fig. 2. Thus, the aforementioned SC requires raw materials (and support materials, if needed), origin and destination entities (e.g., suppliers, warehouses, factories and markets), resources and technologies for transforming materials, and transportation modes (e.g., truck, plane, boat). The problem could be summarily stated as follows:

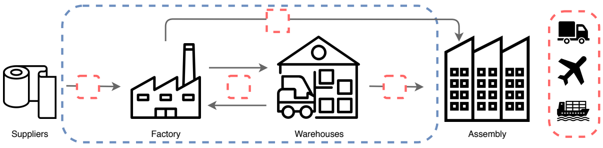

Figure 2: Example of a network structure. Adapted from Mota et al. (2017).

Given:

- A superstructure of interacting entities and respective existing or potentially new geographical locations, composing the supply chain network;
- A set of resources, materials, and time constraints;
- The supply and production capacities;
- A set of alternative manufacturing processes, well characterised and with durations of productive activities;
- The bill of materials, time and resources needed for manufacturing;
- The demand for products being produced;
- A transportation network and transportation means available;
- A fixed time horizon;
- The distance between all points/entities;
- A set of available technologies for manufacturing;
- The fixed/investment and variable costs associated with the whole network (i.e., materials, suppliers, factories, resources, technologies, transportation network, hubs and modes, etc);
- The environmental impacts associated with the whole network (i.e., materials, suppliers, factories, resources, technologies, and transportation activities);
- The social characterisation of the manufacturing processes and transportation activities;
- The initial inventory levels;
- The initial fleet levels;
- The initial resources in given entities.

Determine:

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

In order to:

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

2.1 Case Study

Embraer is a major player in the segment of aircraft up to 100 seats (Regional and Executive Jets). Spread across more than 28 locations, Embraer has presence in Portugal with two plants in Évora and 65% ownership of OGMA in Alverca. This research is interested in the segment of light commercial aviation, in which Embraer accounts for roughly 30% market share and delivered 101 aircraft of their E-series in the year of 2017 (Embraer, 2017).

Regarding Embraer's SC, it is relevant to note the adoption of a typical configuration of a Systems' Integrator model (Santos, 2017). The focal company of this research is a 'Tier 1' supplier, Embraer Portugal located in Évora, and the market is the Original Equipment Manufacturer (OEM) (and parent company), Embraer Brasil located in São José dos Campos. To consider a minimal working example for this case study, and given that Embraer only employs the TA and sources from a single supplier for CFRP raw materials, the two main players in composite materials are considered - Hexcel and Cytec (part of Solvay group). These companies are the leaders in composite material manufacturing and together account for around 80% of the *prepreg* supply market (Santos, 2017). Entities and materials considered in the case study are summarised in tables 1 and 2.

Table 1: Entities in the case study and respective symbols

Entities	Location	Airports	Seaports
Hexcel	Dagneux (FR)	SNA (USA)	Long Beach (USA)
Solvay	Anaheim (USA)	LIS (PT)	Sines (PT)
Embraer	Évora (PT)	SJK (BR)	S.Sebastião (BR)
Embraer	S.J.Campos (BR)	LYS (FR)	Fos-sur-Mer (FR)

Table 2: Raw Materials

Designation	Supplier	Form.	Lot	Unit	Thickness	Density
HexPly M21	Hexcel	TA	190	m^2	0.184 mm	1.58
HiTape HexTow AS7	Hexcel	VARI	100	m^2	0.054 mm	1.79
HexFlow RTM6-2	Hexcel	VARI	46	kg	-	1.11
HexPly M56	Hexcel	VBO	100	m^2	0.194 mm	1.53
Prepreg APC-2-PEEK	Solvay	TS	13	kg	0.16 mm	1.32

2.2 Model Framework

The strategic-tactical nature of the problem points towards the use of optimisation models, which enable decision making considering a SC perspective. The model proposed is an adaptation from Mota et al. (2017) dedicated to SC network design problems. Several steps are required before having on-demand results and figures for analysis, starting always through the process of collecting and treating input data for each objective. This general workflow is depicted in Fig. 3.

2.3 Model Objectives

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

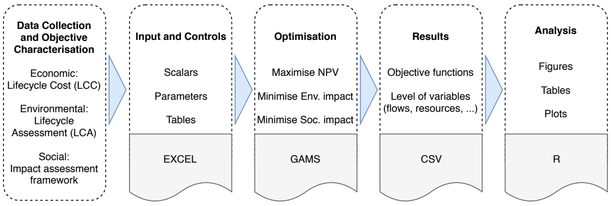

Figure 3: Model framework.

The economic objective function presented here is based on the Net Present Value (NPV), which is precisely the difference between incoming and outgoing cash flows over a period of time. NPV is a common metric if an economical evaluation is performed for non-coincident time periods, meaning the value of cash is not the same at all times and needs to be discounted/normalised for this reason. For the environmental objective, the method of ReCiPE2008 is used to perform the Lifecycle Assessment (LCA) and determine the environmental impact, following the work of Mota et al. (2017) and Santos (2017) with similar goals in terms of impact assessment. The third and last objective function encloses the social aspects of SC performance, known as being the least studied and poorly characterised metric of the Triple Bottom Line (3BL) sustainable performance measures (Barbosa-Póvoa et al., 2018). The poor characterisation and less frequent use of social measures to manage performance in SCs is the motivation for the development of a framework that encompasses this sort of aspects.

After carrying out a more thorough review of specialised literature, several indicators were identified that could represent the social dimension. For this reason, this research makes use of simple qualitative assignments to indicate the absolute difference/distinction of a given process in the named measure, representing if the process has negative, neutral or positive social impact on that same measure. The measures are also selected based on findings from literature and on their relevance. The summary of these measures is presented in table 3.

Table 3: Social impact measures

Measure	Value
Exposure to heat	{-1,0,+1}
Exp. to cold	{-1,0,+1}
Exp. to micro particles/fibres	{-1,0,+1}
Exp. to hazardous gases	{-1,0,+1}
Exp. to noise	{-1,0,+1}
Exp. to high-pressure	{-1,0,+1}
Exp. to mechanic hazards	{-1,0,+1}
Long-period standing	{-1,0,+1}
Handling movements	{-1,0,+1}
Exp. to hazardous/toxic materials	{-1,0,+1}
Man-hours per part	{-1,0,+1}
Additional finishing	{-1,0,+1}
Rework, waste disposal	{-1,0,+1}

2.4 Optimisation Model

This subsection discusses a general structure of the proposed model, its main features and assumptions. For reasons of synthesis, a small version of the mathematical formulation is presented in Appendix A and an extended version can be found in the full-sized document.

Given the limited scope and timeframe for this research, several assumptions and simplifications are required to overcome the problems of lack of data and uncertainty in the estimation of parameters. It is assumed that the finished product does not differ depending on the process. A single batch size parameter, disregard of lead times, transit times or set-up times of any type are all assumptions of the model. It is also assumed materials have no expiry date and there are no restrictions of shelf-life. The production level is equal to demand and this demand not changing over time.

The model proposed includes equations related to demand, manufacturing, the balance of material flowing in and out of the entities, the balance of resources throughout time, entities' capacities, and all aspects regarding transportation. It worth mentioning that technologies are included in resources instead of a separate 'resource', and most constraints are modelled as balance equations of flows and stocks. The possibility to vary the quality rejection rate, to change the scale-up relationships from laboratory to industrial environment and to adapt the batch size for each manufacturing activity are examples of main features of the model. Equations related to manufacturing are key for this model, especially the two equations (3 and 4) that serve to avoid the production of simultaneous products p. In equation 2, production ($P_{i,p,y}$) is constrained by converting the whole equation to time units (hours) and limiting the production by the resources available at that entity. This production level is multiplied by the time and amount of resources r needed to complete a manufacturing activity a (represented by $pTOP_{a,p}$ and $pBOT_{r,p,a}$, respectively), bounded by the available time (in hours) of the resources hired/bought ($R_{r,i,y}$). Besides the general constraints of the model, there are the three objective functions as mentioned earlier.

3 Case Study Results and Discussion

This section aims to present the main results and findings of this research, through the implementation of an optimisation model. A validation of the model and sensitivity analysis for the economic objective are discussed and several other computational experiments are presented, according to each objective function.

The model is implemented in GAMS language, a commonly used system in academia for modelling and solving mixed-integer optimisation problems. Every experiment is carried out on GAMS-IDE v24.9.1 (r63795 WIN-VS8 x86 32bit/MS Windows) running on a OSX v10.11.6 machine equipped with a 1.8 GHz Intel Core i7 processor and 4 GB of RAM (1333 MHz DDR3). Unless indicated otherwise, all computational experiments use the input data specified in the case study, hereafter referred to as the baseline case.

3.1 Model Validation and Sensitivity Analysis

Given the compromise required between model realism and model solvability, validation the model prior to initiating other analyses is critical to ensure that the results are relatively reliable and to establish terms of comparison (Goetschalckx, 2011). The work of Santos (2017) and Marques (2018) for the same forming processes is used to validate the model. The values from Santos (2017) are multiplied by the scale-up relation - 1200 - to obtain the value for the equivalent reference aerostructure. As for results from Marques (2018), these already take into account the aerostructure with the same dimensions and only the base scenarios are considered (2.1.1, 2.2.1, 2.3.1, 2.4.1). Unit costs obtained are analogous to those from Marques (2018), as opposed to results obtained by Santos (2017). In addition, preliminary sensitivity analysis is carried out to better understand how parameters likely to suffer variation would impact the model. This is based on the percentage of deviation from the optimal Net Present Cost (NPC) when variations of -10% and +10% on input parameters are applied. Part length, material price, material thickness, amount of waste, cost of equipment (investment costs) and transportation variable costs are examples of these parameters. The main observation is that those parameters related to quantity of material and material cost have more impact on NPC than other parameters.

3.2 Economic Objective

Considering the baseline case presented in previous chapter, table 4 shows the results on the economic objective function for each forming process, where the lowest value for the NPC is a better and more economical solution. Recall that NPC is symmetric to NPV due to the absence of values for annual revenue, where the goal to maximise NPV corresponds to minimisation of NPC. Based on the assumptions and input parameters considered, the optimal process in terms of the economic objective function is VBO.

Based on the assumptions and input parameters considered, the optimal process in terms of the economic objective function is VBO. These results can be explained essentially by the lower investment costs VBO demands when comparing with TA. Even though VARI and VBO have similar investment costs, as both use the same technologies, VBO requires less raw materials for producing the same part and the costs with labour are lower than those for VARI.

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

Table 4: Economic Results

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

If TS is included in the problem this becomes the new optimal solution for the economic objective. Even though the unit cost of raw materials is higher, the substantially lower quantity needed to produce P4 and the lower costs of technologies makes TS the optimal forming process in this case. However, thermal forming techniques are highly limited in terms of geometries and not yet available for large parts (Land et al., 2015). When looking for manufacturers of machines and tooling, it was only possible to find equipment capable of processing parts as large as 3x4m. Nevertheless, it could be considered the optimal process for smaller parts, as reported by Santos (2017), but before being a possibility in industrial setting more research and technology developments on the process are required.

Having described and discussed the results for the economic objective, more comprehensive analyses impose to better understand the influence of different assumptions and parameters in the overall economic performance. Key factors that are subject to uncertainty or assumed include the (1) scale-up relation between time of process in laboratory and industrial process, (2) demand, (3) batch size and (4) part length. Figure 4 shows the effect on NPC of varying the time scale-up parameter that is used in the model. Scale-up relations and their effect on NPC, and consequently on the optimal forming process, are among the most important features to be studied when selecting the forming process *a priori*. It can also be seen that VARI and VBO present almost a similar linear evolution due to successive increases in production resources for almost every value of the parameter, as opposed to TA that resembles more a step function and for which investment costs in technologies are higher. Regardless of the value 6 being used by Marques (2018), it could be found that a ratio between 2 and 3 would be more close to the actual ratio, after looking into material's data sheets and focusing on total curing cycle times instead of the curing time alone. Considering the longest cure cycle would take 11.25 hours, and from Santos (2017) the total cure cycle time is 5.33 hours. This results in an estimated ratio of 2.11, if the lowest rates for temperature increase and decrease and longest curing time are considered.

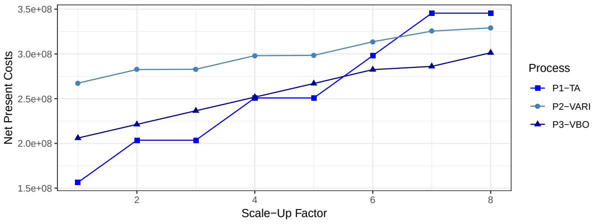

Figure 4: Evolution of NPC with variation of time scale-up factor.

The effect of demand variation on NPC is useful to learn more about each forming process. The fluctuation in unit cost of a reference aerostructure when demand from the OEM changes is shown in figure 5. The general trend towards unit cost reduction is observed, despite the complex relations between different cost factors. In this case, almost all cost factors need to respond to variations in demand, where an increase in demand dictates the purchase of more raw materials, a higher number of trips is required and, most likely, the addition of more resources. Acquisition of technologies and increase in resources is needed in most cases where production capacity needs to increase.

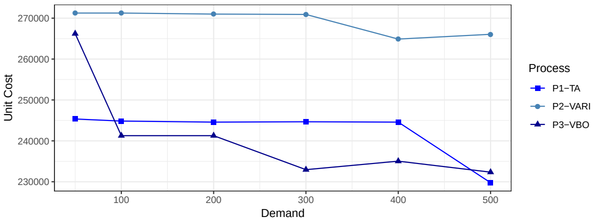

Figure 5: Unit cost when varying the demand.

Results for analysis on batch size are shown in figure 6 and it is possible to learn that TA is now the optimal process for every batch size greater than one. Predictably, the greater the batch size the lower the NPC for all forming processes. After a given value, increasing batch size no longer represents an improvement since equipment and process capacity are no longer the bottlenecks. Note the impact of batch size on NPC is lower than 15% for VARI, whereas for TA this could represent up to 48% reduction in NPC and up to 27% for VBO. Investment costs in technologies define the behaviour of curves presented, as these machines are the biggest bottleneck in composite manufacturing due to relatively long cure cycles. Hence, if more parts can be cured at the same time, less resources are needed and manufacturing costs can be reduced substantially.

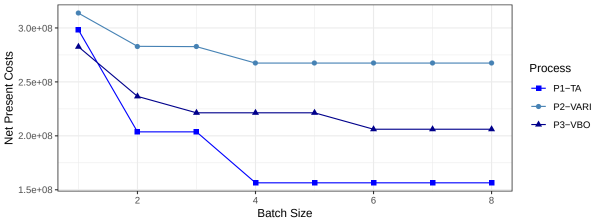

Figure 6: Evolution of NPC with variation of batch size.

As shown previously in the general sensitivity analysis, size of parts being produced also plays an important role in global manufacturing and transportation costs. This effect is depicted in figure 7, where part length is varied from 10 to 20 meters and respective NPC is shown, assuming there are no size limitations throughout the process. These values would rapidly change if different batch sizes were considered, yet this particular analysis is relevant to the problem nevertheless. From this figure alone, VBO appears to be the optimal forming process for all part lengths tested. As expected, the greater the size of parts the higher the NPC, even though the slope is greater for VARI and lower for TA. Overall, NPC for TA appears to be more stable regardless of part size (for the ones considered) and, if needed, VARI should be used for smaller rather than bigger parts.

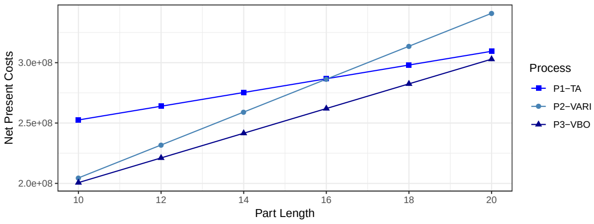

Figure 7: Evolution of NPC with variation of part length.

3.3 Environmental Objective

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

Table 5 shows the results on the environmental objective. Unsurprisingly, TA presents the worst environmental performance mostly due to the use of energy-intensive autoclave curing, whereas both VARI and VBO resort to an oven with much lower impact. The process with the optimal environmental performance is VARI, being the process with the lowest impacts per unit of raw materials. Given the environmental impact for resin infusion is lower than that of producing *prepreg*, not even the greater quantities of raw material needed for VARI and which have to be transported is sufficient to offset the benefits.

Table 5: Environmental Results

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

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

3.4 Social Objective

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

Table 6: Social Results

			P1 - TA	P2 - VARI	P3 - VBO
	Social Impact		18,360	27,540	9,180
Manuf.	Production level		204	204	204
	Material Order		82,910 (RM1)	805,545 (RM2) 27,645 (RM3)	150,369 (RM4)
Res.	Tech.	Oven:	4	4	6
		Vacuum:	4	4	6
	Workforce		1	3	2

As for transportation and technology social impacts, results are almost negligible given the very small values that were arbitrarily assigned to penalise and avoid meaningless model decisions.

According to the framework presented, VBO is the process with a neutral performance on most of harmful social categories. This social impact could be reduced with the support of automation

Table 7: Results

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

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

3.5 General Discussion and Recommendations

Seeing the results from analysis of each objective, general considerations can be drafted regarding the optimal solutions obtained. Here are discussed the optimal solutions for each objective and the decisions made according to different performance measures.

In table 7 are summarised the optimal solutions for each objective. For the economic and social objectives, VBO is the optimal forming process, whereas VARI is the process to go when aiming to minimise environmental impact. These are contrasting objectives given that the process with best environmental performance is the most expensive solution and appeared as global least attractive option throughout the economic analyses.

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

It is important to compare a few values obtained with estimates provided by Embraer. From table 7, it can be verified that costs with raw materials represent between 52% to 68% of total costs, whereas costs with resources fall between 14% and 21%, explaining 66% up to 89% of total cost. According to Embraer, around 51% of unit cost is the average value spent with raw materials and 32% is the amount spent with resources, explaining up to 83% from total cost of one part made out of CFRP. These reference values correspond to a horizontal/vertical stabiliser of Embraer's Legacy 450/500, whose dimensions are different but cost relations are said to be comparable.

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

Several attempts to run a bi-objective optimisation were tried, using both ϵ-constraint and weighted-sum methods. However, the environmental objective function turned out to be too simple and not containing sufficient decision possibilities to generate multiple alternative efficient solutions.

All in all, the recommendation from this research would be to study the adoption of VBO as a promising technology that meets economic performance standards comparable to those of TA. VBO even presents an acceptable environmental impact, much lower than TA. Nevertheless, TA appears to maintain a competitive economic performance and should not be discarded by the industry but rather perfected for better environmental impact.

4 Conclusions and Future Work

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

Engenharia Industrial (Institute of Science and Innovation in Mechanical and Industrial Engineering) (INEGI).

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

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

Finally, some suggestions are made for future work based on findings and knowledge acquired in the present research. It would be of value to broaden the scope of the research and include more aspects and factors to be considered for each objective, namely from other tiers of the SC. A more thorough and accurate characterisation of environmental and social aspects is considered a natural next step, with a focus on more robust impact assessment and scores (e.g., based on exhaustive surveys to industry players).

References

Barbosa-Póvoa, A. P., da Silva, C. and Carvalho, A. (2018), 'Opportunities and challenges in sustainable supply chain: An operations research perspective', *European Journal of Operational Research* .

Embraer (2017), Annual Report 2017, Technical report.

European Commission (2011), Flightpath 2050 - Europe's Vision for Aviation, Technical report.

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

Goetschalckx, M. (2011), *Supply Chain Engineering*, Vol. 161 of *International Series in Operations Research & Management Science*, Springer US, Boston, MA.

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

Marques, A. (2018), Sustainable Alternatives for Logistics in Aerospace, Thesis, Instituto Superior Técnico.

Mota, B., Gomes, M., Carvalho, A. and Barbosa-Póvoa, A. (2017), 'Sustainable supply chains: An integrated modeling approach under uncertainty', *Omega* **0**, 1–26.

Santos, D. H. (2017), Caracterização e Otimização da Cadeia de Abastecimento Aeronáutica O caso da Embraer, Thesis, Instituto Superior Técnico.

A Appendix A - Mathematical Formulation

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

A.1 General Model

Table 8: Sets and indexes

Index		Set	
i, j	Locations	L	$= L_{sup} \cup L_f \cup L_c \cup L_{air} \cup L_{port}$ $= L_{REG1} \cup L_{REG2} \cup L_{REG3}$
i	Focal entity		
j	Third party		
		L_{sup}	Suppliers
		L_f	Factories
		L_c	Customers
		L_{air}	Airports
		L_{port}	Seaports
z	Transp. modes	Z	$= Z_{truck} \cup Z_{plane} \cup Z_{boat}$ $= Z_{cool} \cup Z_{nocool}$
		Z_{truck}	Truck
		Z_{plane}	plane
		Z_{boat}	boat
		Z_{cool}	Transp. with cooling
		Z_{nocool}	Transp. without cooling
r	Resources	R	$= R_{tech} \cup R_{labour}$
		R_{tech}	Production technologies
		R_{labour}	Labour
m	Materials	M	$= M_{raw} \cup M_{product}$
		M_{raw}	Raw materials
		$M_{products}$	Finished products
		M_{mat}	Manufacturing materials
		M_{nocool}	Non-cooled materials
		M_{cool}	Cooled materials
p	Products		$p \equiv m \in M_{products}$
		N	Full network connections
		N_{NET}	Allowed connections
		$N_{OUT_{i/x}}$	Outbound flow
		$N_{IN_{i/x}}$	Inbound flow
t	Period (micro)		
y	Period (macro		
a	Manuf. activity		
γ		Γ	Type of investments
λ		Λ	Env. Midpoint Categories
ψ		Ψ	Social categories

Table 9: Decision Variables

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

Table 10: Parameters

General Parameters:	
$batch_{a,p}$	Batch size for activity a in process p
$bigM$	Big enough value
$d_{i,t}$	Demand of product by customer in location i in period t
$dist_{lo,ld}$	Distance between lo and ld
$drvHrsWk^{max}$	Maximum driving hours per week
$invTruck^{max}$	Maximum investment in trucks
$learningCurve_{r,y}$	Learning curve, alternative to productivity
lot_m	Lot size for material m
$nomWg_m$	Nominal weight of material m
$pBOM_{mat,p}$	Bill of materials mat for process p
$pBOT_{r,p,a}$	Bill of resources r for process p in activity a
$prod_r$	Productivity of resource r
$prodArea_m$	Area occupied by material/product m
$prodWeight_m$	Weight of material/product m
$pTOP_{a,p}$	Duration of activity a for process p
$rejRate$	Rejection rate for finished parts with quality issues
$scaleUp_{a,p}$	Time scale-up factor for activity a in process p
$scaleUpMult$	Scale-up multiplier based on area from testbed
$supCapacity_i$	Max capacity of supplier i
$t_{h/shift}$	Number of hours per shift
$t_{shifts/d}$	Number of shifts per day
$t_{ds/mth}$	Number of working days per month
$t_{mths/yr}$	Number of month in a year
$tAcquire_z$	Cost of acquiring mean z
$tCap^{min}_z$	Minimum capacity of transportation mode z per time period
$tCapMat^{max}_z$	Material capacity of transportation mode z in weight per time period
$tCapProd^{max}_z$	Product capacity of transportation mode z in units per time period
$tCont^{max}_z$	Annual maximum number of trips contracted for mode z
$trAvgS$	Truck average speed
v^{avg}	Average speed of vehicle
$wkTime$	Number of weeks per time period (month)

$$\sum_{\substack{p\\ j\in F_{IN_{c/fp}}\\ z\in N_{NET}}} X_{j,i,p,z,y} = \sum_t d_{i,t} \cdot \frac{1}{(1-rejRt)} \qquad , \forall\, y, i \in L_c \tag{1}$$

$$\sum_a \frac{pBOT_{r,p,a} \cdot pTOP_{a,p}}{batch_{a,p}} \cdot scaleUp_{a,p} \cdot P_{i,p,y} \leqslant prod_r \cdot R_{r,i,y} \cdot t_{h/shift} \cdot t_{shifts/d} \cdot t_{ds/mth} \cdot t_{mths/yr} \qquad , \forall\, i, p, r, y \tag{2}$$

$$\sum_y \sum_t P_{i,p,t,y} \leqslant bigM \cdot \Omega_p \qquad , \forall\, i \in L_f, p \tag{3}$$

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

$$R_{r,i,(y-1)} + AddR_{r,i,y} - CutR_{r,i,y} = R_{r,i,y} \qquad , \forall\, r, i, \{y \in Y : y > 1\} \tag{5}$$

$$S_{i,m,(y-1)} + \sum_{\substack{j\in F_{IN_{wh/x}}\\ z\in N_{NET}}} X_{j,i,m,z,y} = S_{i,m,y} + \sum_{\substack{j\in F_{OUT_{wh/x}}\\ z\in N_{NET}}} X_{i,j,m,z,y} \qquad , \forall\, m, \{y \in Y : y > 1\}, i \in L_w \tag{6}$$

$$S_{i,p,y-1} + P_{i,p,y} = S_{i,p,y} + \sum_{\substack{j\in F_{OUT_{f/fp}}\\ z\in N_{NET}}} X_{i,j,p,z,y} \qquad , \forall\, p, i \in L_f, \{y \in Y : y > 1\} \tag{7}$$

$$S_{i,m,y-1} + \sum_{\substack{j\in F_{IN_{f/rm}}\\ z\in N_{NET}}} X_{j,i,m,z,y-1} = S_{i,m,y} + \sum_{\substack{p\\ j\in F_{OUT_{wh/fp}}\\ z\in N_{NET}}} pBOM_{m,p} \cdot scaleUpMult \cdot P_{i,m,y} \qquad , \forall\, m \in M_{mat}, i \in L_f, \{y \in Y : y > 1\} \tag{8}$$

$$\sum_{z\in N_{NET}} X_{i,j,m,z,t,y} = lot_m \cdot PO_{i,j,m,y} \qquad , \forall\, m \in M_{mat}, i, j, y \tag{9}$$

$$\sum_{\substack{j\in F_{IN_{air/x}}\\ z\in N_{NET}}} X_{j,i,m,z,y} = \sum_{\substack{j\in F_{OUT_{air/x}}\\ z\in N_{NET}}} X_{i,j,m,z,y} \qquad , \forall\, m, i \in L_{air}, y \tag{10}$$

$$\sum_{\substack{j\in F_{IN_{port/x}}\\ z\in N_{NET}}} X_{j,i,m,z,y} = \sum_{\substack{j\in F_{OUT_{port/x}}\\ z\in N_{NET}}} X_{i,j,m,z,y} \qquad , \forall\, m, i \in L_{port}, y \tag{11}$$

$$tCapMat^{max}_z \cdot T_{z,i,j,y} \geqslant \sum_{\substack{m\in M_{mat}\\ m\in N_{NET}}} nomWg_m \cdot X_{i,j,m,z,y} \qquad , \forall\, z, (i,j) \in N_{ALL}, y \tag{12}$$

$$tCapProd^{max}_z \cdot T_{z,i,j,y} \geqslant \sum_{p\in N_{NET}} X_{i,j,p,z,y} \qquad , \forall\, z, (i,j) \in N_{ALL}, y \tag{13}$$

$$tCap^{min}_z \cdot T_{z,i,j,y} \leqslant \sum_{m\in N_{NET}} X_{i,j,m,z,y} \qquad , \forall\, z, (i,j) \in N_{ALL}, y \tag{14}$$

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y}$$
$$, \forall\, z \in (Z_{boat} \cup Z_{plane}), (i,j) \in N_{ALL}, y \tag{15}$$

$$T_{z,i,j,y} \leqslant tCont_z^{max} \cdot \zeta_{z,y}$$
$$, \forall\, z \in Z_{truck}, (i,j) \in N_{ALL}, y \tag{16}$$

$$Tr_{z,i,y}^{period} = \frac{\sum_{j \in N_{intra}} (2 \cdot dist_{i,j} \cdot T_{z,i,j,y})}{v^{avg} \cdot drvHrsWk^{max} \cdot wkTime}$$
$$, \forall\, z \in Z_{truck}, i, y \tag{17}$$

$$F_{z,i,y} \geqslant Tr_{z,i,y}^{period}, \forall\, z \in Z_{truck}, i, y \tag{18}$$

$$\sum_{\substack{i \in N_{NET} \\ z \in Z_{truck}}} tAcquire_z \cdot BuyT_{z,i,y} \leqslant invTruck^{max}, \forall\, y \tag{19}$$

$$\sum_{\substack{j \in N_{NET} \\ j \notin L_{air} \\ z \notin Z_{plane}}} X_{j,i,m,z,y} = \sum_{\substack{j \in N_{NET} \\ j \in L_{air} \\ z \in Z_{plane}}} X_{i,j,m,z,y}$$
$$, \forall\, m, i \in L_{air}, y \tag{20}$$

$$\sum_{\substack{j \in N_{NET} \\ j \notin L_{port} \\ z \notin Z_{boat}}} X_{j,i,m,z,y} = \sum_{\substack{j \in N_{NET} \\ j \in L_{port} \\ z \in Z_{boat}}} X_{i,j,m,z,y}$$
$$, \forall\, m, i \in L_{port}, y \tag{21}$$

$$\sum_j PO_{i,j,m,y} \leqslant supCap_i \cdot \Theta_i$$
$$, \forall\, m \in M_{mat}, i \in L_{sup}, y \tag{22}$$

$$\sum_{(m,z,j) \in N_{NET}} X_{j,i,m,z,y} \leqslant bigM \cdot \Theta_i$$
$$, \forall\, i \notin L_{sup}, y \tag{23}$$

$$\sum_{(m,z,i) \in N_{NET}} X_{i,j,m,z,y} \leqslant bigM \cdot \Theta_j$$
$$, \forall\, j \notin L_{sup}, y \tag{24}$$

A.2 Economic Objective Function

Table 11: Economic Auxiliary Variables

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

Table 12: Economic Auxiliary Parameters

Economic Parameters:	
avC_z	Average fuel consumption of mode z
fp	Fuel price
$vhcMntc_z$	Maintenance of mode z
$cContract_z$	Cost of contract w/ carrier for mode z
$matP_{m,i}$	Price of material m from supplier i
$hubVarC_i$	Variable cost at hub i
$holdC_m$	Holding cost of material m
$cellC_{m,i}$	Install cell for material m at i
$kmRt$	Rate per kilometer
$tripRt_z$	Rate per trip for mode z
sv_γ	Salvage value of investment γ
$discRt$	Discount rate
$taxRt$	Tax rate
inv_i^x	Investment cost at location i

maximise $$NPV = \sum_y \left(\frac{CF_y}{(1 + discRt)^{(y)}} \right) - \sum_\gamma FCI_\gamma \tag{25}$$

$$FCI_\gamma = \begin{cases} \displaystyle\sum_{i \in L_f \cup L_w} (inv_i^{facility} + inv_i^{others}) \cdot \Theta_i, \quad \gamma = 1 \\ \displaystyle\sum_p \Big[\sum_{\substack{y \\ m \\ r \in R_{tech}}} (inv_r^{equip} \cdot AddR_{r,i,y}) \\ +(inv_p^{tooling} \cdot \Omega_p)\Big], \quad \gamma = 2 \\ \displaystyle\sum_{z \in Z_{fleet}} \sum_i inv_z^{truck} \cdot BuyT_{z,i,y}, \quad \gamma = 3 \end{cases} \tag{26}$$

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

$$CF_y = \begin{cases} NE_y & , \quad t = 1, \ldots, NT - 1 \\ NE_y + \sum_\gamma (sv_\gamma \cdot FCI_\gamma) & , \quad t = NT \end{cases} \tag{27}$$

NT is the last period

$$DC_y = \sum_\gamma DP_{\gamma,y} \cdot FCI_\gamma \tag{28}$$

$$\begin{aligned} NE_y = {} & (1 - taxRt) \cdot \Big[annualRevenue_y \\ & - \sum_y \Big[\sum_{m,i,j} (matP_{m,i} \cdot lot_m \cdot PO_{i,j,m,y}) \\ & + \sum_{\substack{i \\ r \in R_{labour}}} [(fireC_r \cdot CutR_{r,i,y} + hireC_r \cdot AddR_{r,i,y}) \\ & + (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y})] + \\ & \sum_{\substack{i \\ r \in R_{tech}}} (resRt_r \cdot R_{r,i,y} \cdot t_{hrs/st} \cdot t_{sts/d} \cdot t_{ds/mth} \cdot t_{mths/y}) \\ & + \sum_{i,j,m} (\sum_z (cContract_z \cdot \zeta_{z,y})) \\ & + \sum_{z \in Z_{truck}} ((\frac{avC_z}{100} \cdot fp + vhcMntc_z) \cdot 2 \cdot dist_{i,j} \cdot T_{z,i,j,y}) \\ & + \sum_{z \in Z_{plane} \cup Z_{boat}} ((tripRate_z + kmRt \cdot dist_{i,j}) \cdot T_{z,i,j,y}) \\ & + \sum_{j,i \in L_{mtp}} (hubVarC_i \cdot (X_{i,j,m,z,y} + X_{j,i,m,z,y})) \\ & + \sum_{i,m} (cellC_{m,i} \cdot CellsOpen_{i,y} + holdC_m \cdot S_{i,m,y})\Big]\Big] \\ & + \Big(taxRt \cdot DC_y\Big) \end{aligned} \tag{29}$$

A.3 Environmental Objective Function

minimise $EnvImpact$

$$\begin{aligned} = {} & \sum_{\substack{\lambda \\ y}} normF_\lambda \cdot \Big[\sum_{\substack{p \\ a \\ i \in L_f}} (envFact_{\lambda,r}^{tech} \cdot pBOT_{r,p,a} \cdot pTOP_{a,p} \cdot P_{i,p,y}) \\ & + \sum_m \sum_{(i,j)} (matFootprint_{\lambda,m,i}^{supplier} \cdot lot_m \cdot PO_{i,j,m,y}) + \\ & \sum_{\substack{z \\ (m,i,j) \in N_{NET}}} (envFact_{\lambda,z}^{transp} \cdot nomWg_m \cdot dist_{i,j} \cdot X_{i,j,m,z,y}) \\ & + \sum_m \sum_{i \in (L_f \cup L_w)} (envFact_{\lambda,m}^{storage} \cdot S_{i,m,y}) \\ & + \sum_{i \in (L_f \cup L_w)} (envFact_{\lambda,i}^{entity} \cdot \Theta_i)\Big] \end{aligned} \tag{30}$$

A.4 Social Objective Function

minimise $SocImpact$

$$\begin{aligned} = {} & \sum_\psi \sum_y normFact_\psi \cdot \Big[\sum_{p,a} \sum_{i \in L_f} (socFact_{\psi,r}^{manuf} \cdot P_{i,p,y}) \\ & + \sum_m \sum_{(i,j)} (matSocFootprint_{\psi,m,i}^{supplier} \cdot lot_m \cdot PO_{i,j,m,y}) \\ & + \sum_{(m,i,j) \in N_{NET}} \sum_z (socFact_{\psi,z}^{transp} \cdot T_{z,i,j,y}) \\ & + \sum_m \sum_{i \in (L_f \cup L_w)} (socFact_{\psi,m}^{storage} \cdot S_{i,m,y}) \\ & + \sum_{i \in (L_f \cup L_w)} (socFact_{\psi,i}^{entity} \cdot \Theta_i)\Big] \end{aligned} \tag{31}$$