EXECUTIVE SUMMARY OF THE THESIS

Evaluating the Impact on Supply Chain Relocation of Chinese Manufacturers under Equivalent Tariff: A Simulation-Based Study

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

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1. Introduction

In recent years, global supply chains have been increasingly affected by rising geopolitical tensions and trade conflicts [1]. In particular, the escalation of trade wars has led to significant rise in tariffs, directly impacting the cost structures of internationally distributed supply networks. A notable example is the increase in customs duties imposed by the United States on imports from China, which has substantially altered production and sourcing costs for firms operating across borders. To remain competitive under these conditions, companies must carefully evaluate the impact of tariff burdens alongside other cost components, such as production, transportation, labour, and energy [2]. At the same time, environmental sustainability has emerged as a critical concern, as carbon emissions have attracted growing attention from governments and regulatory bodies seeking to mitigate climate change and safeguard long-term economic and environmental stability [3]. In addition to cost efficiency and environmental performance, service level has become a key competitive factor, increasingly viewed as an order-winning criterion essential for both attracting new customers and retaining existing ones. These evolving priorities have transformed supply chain design into a complex, multi-objective decision problem, particularly as modern supply chains have become more globalized and interconnected, often resembling networks rather than linear chains [4]. In this context, evaluating the effects of tariffs and exploring alternative supply chain configurations are essential to improving economic performance, enhancing supply chain resilience, and reducing environmental impacts in an increasingly uncertain global environment. Accordingly, this study examines the relocation of supply chain actors under the current trade-war scenario, explicitly considering economic, environmental, and service-level objectives.

The paper first develops an optimization model to represent the supply chain structure and its objectives; however, such a model alone cannot fully capture the multiple sources of variability that play a critical role in complex supply chain networks. To address this limitation, a simulation model is subsequently developed to incorporate different sources of uncertainty and operational variability. The combined optimization–simulation framework is validated through case studies and is used to identify suboptimal relocation and allocation strategies that enable firms to achieve competitive advantages by minimizing costs and emissions while considering the service level.

2. Literature Review

To support the development of this study, a focused review of the existing literature has been conducted. Given the nature of the research, the literature is organised into two main streams: optimization models and simulation models addressing supply chain location and allocation problems. A comprehensive analysis of 65 papers has been carried out where the relevant studies were identified using keywords such as *supply chain design*, *location and allocation*, *optimization*, *simulation*, and *equal tariffs*, primarily through the Scopus database.

2.1. Optimization

Optimization models have been extensively used in supply chain research to address uncertainty, risk, and strategic decision-making related to procurement, production, and network design.
Facility location and allocation problems have been extensively investigated using optimization approaches, predominantly focusing on cost-related drivers [5, 6].
On top on that, improving resilience from the supplier's perspective is widely recognised as critical for maintaining supply chain continuity, as upstream disruptions strongly affect overall performance [7], and procurement-related decisions have been identified as among the most disruptive elements of supply chains [8]. Several studies incorporate risk and uncertainty directly into optimization frameworks, with the most addressed factors including delivery delays, exchange rate fluctuations, quality issues, logistics failures, and production disruptions [9, 10, 11]. However, global and policy-related factors are far less frequently considered in the optimization literature; for example, exchange rates and tariffs are only sporadically incorporated, appearing in very few studies [12].
Overall, the optimization literature shows a strong emphasis on cost minimization, risk management, and facility location decisions.

2.2. Simulation

The most recurring objective in simulation-based supply chain studies is the minimization of total cost, or, in some cases, the maximization of profit, both of which are directly related to firms' financial performance [13, 14]. In contrast, the minimization of environmental impact appears less frequently in the analysed literature and is addressed in only a limited number of studies compared to purely economic objectives [15]. The maximization of demand fulfilment, closely related to service level performance, is the least frequently considered objective, and its sporadic presence highlights a relevant research gap despite its growing importance in competitive supply chain environments [16]. With respect to methodological approaches, Mixed-Integer Linear Programming (MILP) clearly emerges as the dominant modelling technique, appearing in more than 50% of the reviewed studies when an optimization model is developed prior to simulation, often combined with Monte Carlo or fuzzy-based simulation methods for solution or validation. Discrete Event Simulation (DES) is less frequently employed but remains relevant when process-level dynamics and time-dependent events are central [15, 16], while Agent-Based Simulation (ABS) appears only sporadically, as it is most suitable for contexts involving interactions among autonomous agents, which are not always required in traditional supply chain modelling, although it offers high modelling flexibility when such interactions are present [17]. Metaheuristic methods, including genetic algorithms and other evolutionary techniques, are widely adopted to manage increasing model complexity and obtain near-optimal solutions within reasonable computational times. Regarding decision variables, manufacturing costs are almost universally included, yet only a small number of studies disaggregate these costs into detailed components such as labour and energy [18, 17], with energy costs explicitly modelled as a separate driver in only one study [19]. Transportation costs and capacity constraints are considered in nearly all papers, whereas penalty costs, taxes, and customs duties are rarely incorporated, with only Eroglu [14] and Mishra and Singh [20] explicitly integrating tariffs. Disruptions also receive limited attention: Safari et al. [15] model transportation delays due to congestion and adverse weather, while Eroglu [14] incorporates disruptions in production and transportation through sensitivity analysis. Finally, most simulation models focus exclusively on local production settings, with relatively few studies extending the analysis to international production location decisions, as reported by Bhowmik et al. [18].

2.3. Research Gap

Despite the growing body of literature on supply chain optimisation and simulation, several relevant gaps remain, particularly in the context of global supply chains operating under trade-war conditions. One of the most significant omissions concerns the explicit integration of tariffs and customs duties into simulation-based supply chain models: although some studies address global scenarios, tariff structures are rarely treated as endogenous decision variables, despite their increasing influence due to ongoing trade conflicts and rising protectionist policies. Moreover, most existing simulation models focus on local or regional supply chains, which are inherently less complex and easier to model, while fully global configurations, characterised by cross-border production, international sourcing, and long-distance transportation, are comparatively underrepresented, limiting the ability of current models to capture the operational and financial challenges faced by globally distributed networks. Another important gap relates to cost representation, as key cost drivers are often aggregated into broad categories such as total production or logistics cost, thereby obscuring the individual contribution of specific components including labour, energy, building costs, penalty costs associated with unmet demand, and customs-related charges. Finally, although sustainability considerations have gained increasing attention, only a limited number of studies jointly analyse economic and environmental objectives within a unified modelling framework, and the simultaneous evaluation of total cost and carbon emissions in a global, tariff-sensitive supply chain context remains relatively unexplored. Taken together, these limitations define a clear research gap that this study addresses by developing a global supply chain optimisation–simulation framework explicitly incorporating tariff structures, detailed cost drivers, penalty mechanisms, and multiple objectives, including cost minimisation and emissions reduction.

3. Research Objectives

The study is guided by two main research objectives that address the strategic decisions faced by firms operating global supply chains under trade-war conditions. Specifically, the study is developed to:

i) evaluate the relative advantages of alternative production facility locations.

The first research goal focuses on the facility location problem and aims to identify the most advantageous production location for firms operating under the conditions imposed by the ongoing trade war.

Three location scenarios are considered:

1. **Local site** (China)
2. **Market site** (United States)
3. **Third-country site** (Americas, Asia, Europe)

The presence of seaports is treated as a mandatory requirement, as maritime transportation represents the most cost-effective mode compared to air freight and plays a central role in global supply chain operations.

ii) determine optimal supplier selection and procurement allocation strategies.

The second research goal addresses the firm's sourcing strategy and focuses on determining the optimal allocation of procurement volumes among alternative suppliers. Given the global nature of the supply network and the impact of tariffs on upstream flows, sourcing decisions are expected to significantly influence total costs, carbon emissions, and service performance.

Procurement strategies are therefore modelled through three alternative sourcing configurations:

1. **Local sourcing** (OEM's home country)
2. **Market sourcing (**United States)
3. **Global sourcing** (third-party countries)

These sourcing decisions are evaluated in combination with production location choices and are analysed through key decision variables, including purchased quantities, sourcing proportions, raw material prices, and applicable tariff rates.

3.1. Complementary Use of Optimization and Simulation

To address the research objectives, optimization and simulation are used as complementary approaches for supply chain design. The optimization model defines the strategic decision context by identifying optimal production locations, sourcing strategies, and performance trade-offs, explicitly maximizing service level alongside minimizing cost and emissions. Building on this framework, a simulation model is used to evaluate these decisions under realistic operational conditions by representing time-dependent processes, inventory dynamics (Figure 1), and transportation delays that cannot be fully captured in the static optimization model. In the simulation, the objective focuses on minimizing cost and emissions, while service level is not directly optimized but is considered in the interpretation of results.

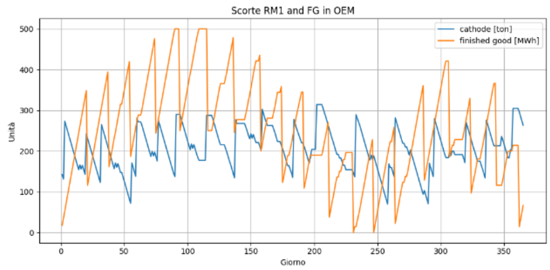

Figure 1 Inventory dynamics

4. Optimization Model

4.1. System description

The optimization model addresses single-site and multi-site production location decisions under dynamic tariff regimes and normalized risks. Manufacturing sites are selected from three alternatives, such as local (L), market (M), and third-party (T), while jointly optimizing raw-material sourcing to balance total cost minimization, carbon-emission reduction, and service-level maximization. Demand is continuous and stochastic, and production relies on multiple raw materials that can be sourced locally, regionally, or globally. Transportation is subject to disruption risk and involves different modes with heterogeneous cost and emission profiles. Production capacity is affected by dynamic risk factors and evolves across three states (normal operation, partial disruption, and full shutdown) modelled through a Markov state-transition process (Figure 2).

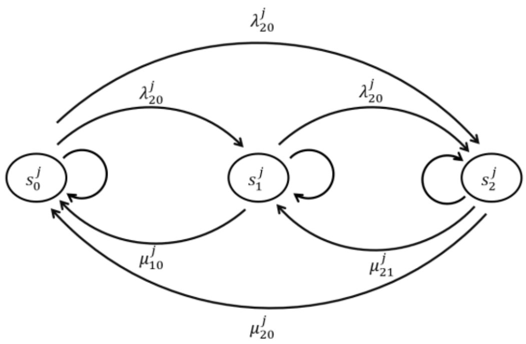

Figure 2 Markov Chain

Mathematical Formulation

The basic (single-site) and extended (multi-site) formulations share the same three objectives; the extended model differs only by allowing multiple plants and allocation across them.

1) Minimise expected total cost

$$\min ETC = CC + PC + TC + PTC + SC$$

where ETC is the expected total cost over the horizon, composed of comprehensive (fixed) costs CC, production costs PC, transportation costs TC, procurement and tariff costs PTC, and stockout/penalty costs SC.

2) Minimise total carbon emissions

$$\min CE = EPR + EPF + ETR + ETF$$

where EPR represents emissions from raw-material production/processing (suppliers), EPF emissions from final product production at the OEM (electricity-related), ETR emissions from transporting raw materials to the OEM, and ETF emissions from transporting finished goods to the distribution centre.

3) Maximise service level

$$\max SL = \frac{1}{Time} \sum_{t=1}^{Time} \left(\frac{Q_t^{del}}{D_t} \right)$$

with delivered quantity defined as:

$$Q_t^{del} = \sum_{j \in \{L,M,T\}} \bar{Q}_t^j \; Tpro^j \, X^j$$

where D_t is demand in period t, and $\bar{Q}_t^j Tpro^j X^j$ represents the effective output delivered from site j in period t.

5. Simulation Model

5.1. Conceptual Model

As defined in the optimization model, the supply chain considered in this study has two alternative configurations: a basic single-site model and an extended multi-site model. In both cases, the system is represented as a three-echelons supply chain consisting of upstream suppliers, a central original equipment manufacturer (OEM), and a downstream distribution centre responsible for fulfilling final market demand, with the OEM operating either one production plant in the basic model or two geographically distributed plants in the extended model. The supply chain operates under a make-to-stock (MTS) policy, where production and replenishment decisions are triggered once inventory levels reach a predefined reorder point, and unmet demand is recorded and penalised according to the model's cost structure. Uncertainty and variability are explicitly incorporated at multiple stages: final customer demand follows a normal distribution with mean μ and standard deviation σ, transportation disruptions arise from adverse weather conditions and congestion at critical maritime chokepoints such as the Panama and Suez Canals, and production disruptions at OEM plants are modelled dynamically through a Markov chain. Geographical eligibility for suppliers and production plants is constrained by proximity to seaports, reflecting the central role of maritime transportation in global supply chains, while intermodal transportation is adopted when direct port access is not available.

5.2. Model implementation

The simulation environment is represented as a network of interconnected nodes, where links correspond to maritime routes among the ports under analysis and define the feasible sea-routes for material flows. **Shipments** are modelled as passive objects representing the movement of both raw materials and finished goods between supply chain actors, while accounting for transportation time, cost, and associated carbon emissions. **Suppliers** are modelled as Agents responsible for providing the required quantities of raw materials to the OEM plants in response to incoming orders. The **OEM** Agent represents the manufacturing entity and manages production, inventory control, and replenishment decisions, as well as the delivery of finished goods to the downstream distribution centre; within this agent, production capacity is dynamically modelled through the Markov chain. The **Distribution Centre** (DC) Agent receives finished goods from OEM plants and fulfils final customer demand by monitoring inventory levels, recording unmet demand when stock is insufficient, and evaluating reorder point conditions to place replenishment orders to the OEM plants. Transportation processes and related uncertainties are handled by the **Carrier** Agent, which manages shipment movements along the defined sea-routes, explicitly models disruptions by introducing stochastic delays and continuously checks shipment arrival status.

5.3. Genetic Algorithm and Validation

Each case study is characterised by a distinct dataset reflecting industry-specific cost structures, demand patterns, and operational parameters. To solve the optimisation problem, a Genetic Algorithm (GA) is employed as the primary search and solution method. To account for stochastic variability across simulation runs and to support the GA in identifying robust near-optimal solutions, each supply chain configuration is evaluated through five independent simulation runs. The resulting KPIs are subsequently averaged to obtain representative performance measures for each scenario. A validation phase is then conducted to assess the robustness and stability of the results. The analysis confirms that in most of the cases, five simulation runs per scenario are sufficient to stabilise the KPI values and ensure consistency across repetitions. Based on these findings, the GA parameters adopted for both the basic single-site model and the extended multi-site model are reported in Table 1.

Table 1 GA parameters

GA parameter	Single-site	Multi-site
Population size	20	35
Max iterations	50	50
Mutation probability	0.1	0.1
Crossover probability	0.8	0.8
Max iterations without improvements	15	15

6. Results

Data for this study were collected from multiple sources to ensure both realism and consistency across analyses. OEMs' information was obtained directly from company managers as well as from publicly available corporate reports. Data on supplier energy consumption were based on reasonable assumptions. Country-level data, including labour costs, land costs, energy prices, ECEF, tariffs, and distances between ports, were retrieved from government's websites and reliable international databases. Based on this, simulations with time horizon of one business year were run: two case studies are analysed to validate the proposed simulation model and to generate analytical insights into the impact of tariffs, cost structures, and sustainability objectives on supply chain design decisions. The first focuses on the high-technology sector, represented by the power batteries industry, which is characterised by high capital intensity, complex sourcing requirements, and significant environmental implications. The second examines the consumer goods sector, using outdoor apparel as a representative product category, where cost competitiveness and operational flexibility are critical.

6.1. Power Batteries

The results of the Power Batteries case study highlight the strong and combined impact of tariff regimes, energy costs, and environmental factors on optimal supply chain configuration in high-technology, energy-intensive industries. Under the equal-tariff regime, simulation outcomes consistently show that production strategies concentrated in China are no longer economically viable, despite traditional advantages in labour and land costs. In the single-site baseline scenario, with production located in China, total cost reaches **352.09 M USD**, while total emissions amount to **110,743 tCO_2e**, making this configuration the worst performer on both objectives. High tariffs play a decisive role: power batteries exported from China to the U.S. are subject to a **35.90%** duty, while alternative locations face tariffs of only **3.40%**, and imported raw materials in the Chinese scenario are subject to an additional **25%** tariff, largely offsetting China's production cost advantage (Figure 3). European production locations emerge as environmentally favourable due to their low electricity carbon emission factors; for example, the emissions-minimizing configuration relocates production to Spain, reducing total emissions to **35,463 tCO_2e**, corresponding to a reduction of 68**%** relative to the baseline, albeit at a higher total cost of **193.80 M USD**. This pronounced environmental advantage is explained by the energy-intensive nature of power battery manufacturing, where electricity consumption in production dominates the overall carbon footprint, creating a large gap between production emissions and transportation emissions across all scenarios [21]. Transportation emissions remain relatively similar and comparatively small because maritime shipping, which dominates logistics flows, has low emissions per ton-mile (Figure 4). Asian countries' solutions different from China, partially reduce tariff exposure but remain disadvantaged by long transportation distances and increased logistical complexity, which limit both economic and environmental gains. In contrast, configurations that allocate a substantial share of production capacity in Latin America, close to Chilean and Argentinian suppliers, deliver the most balanced performance, particularly in the advanced multi-site model, combining lower total costs, reduced tariff exposure, improved service levels, and greater resilience to disruptions.

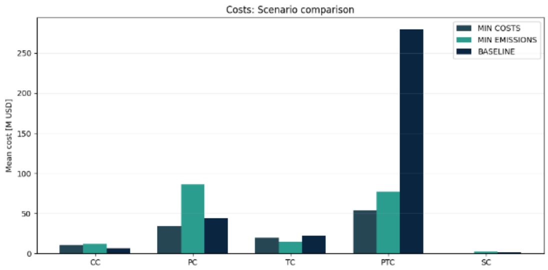

Figure 3 Cost drivers Power Batteries

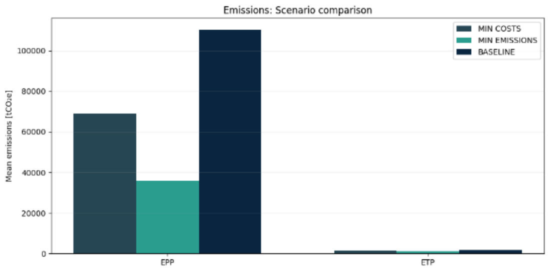

Figure 4 Emission drivers Power Batteries

6.2. Outdoor Apparel

In the Outdoor Apparel case study, the structure of the industry strongly influences both environmental and economic outcomes, leading to results that differ from the Power Batteries case. OEM manufacturing plants in this sector are not energy-intensive, as final assembly activities are mainly limited to cutting, sewing, and finishing operations; consequently, the direct environmental impact associated with the production phase is relatively low across all location scenarios. The largest share of emissions originates upstream, during the processing and production of raw materials such as technical fabrics and synthetic fibres, implying that supplier location and sourcing strategies are the primary determinants of environmental performance rather than the geographical placement of the OEM plant. Transportation-related emissions are also comparatively limited because outdoor apparel products are lightweight and efficiently transported, even over long distances via maritime shipping (Figure 6). From a cost perspective, however, transportation remains a relevant driver due to the long intercontinental routes involved, despite its modest environmental contribution. Tariffs play a secondary role, as apparels are generally lower cost items compared to power batteries, which limits their overall impact in a consumer goods supply chain (Figure 5). These structural characteristics explain why the baseline China configuration is strongly dominated in terms of total cost: in the single-site model, the China baseline yields a total cost of **43.37 M USD**, while the cost-minimizing solution relocates production to the United States, reducing total cost to **10.37 M USD** and improving service level. In the multi-site model, the China baseline remains unchanged at **43.37 M USD**, whereas the optimized dual-site configuration, primarily based in the United States with a secondary allocation in South Korea, reduces total cost to **14.14 M USD** and achieves a higher service level, confirming the advantage of proximity to final markets and diversified production in mitigating transportation and procurement-related costs. Overall, the Outdoor Apparel results demonstrate that, in low-energy and low-weight industries, total cost optimization is driven mainly by transportation economics and sourcing patterns rather than by production energy consumption or tariff exposure, reinforcing the importance of upstream decisions and market proximity in global supply chain design.

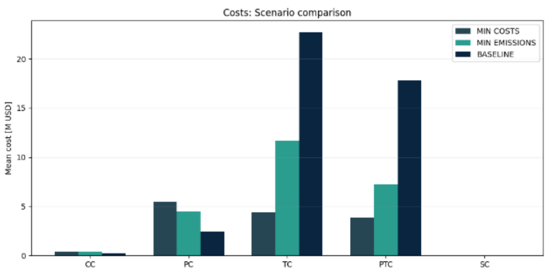

Figure 5 Cost drivers Outdoor Apparel

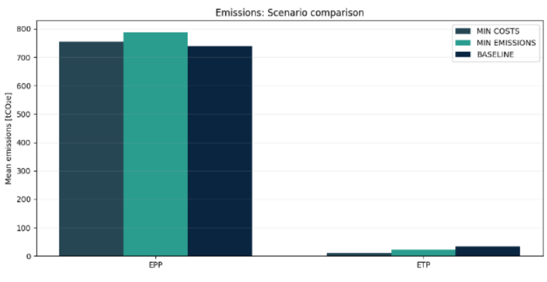

Figure 6 Emission drivers Outdoor Apparel

7. Conclusion

This thesis investigated how global supply chains should be configured under an equal-tariff regime by analysing two case studies representing structurally different industries: power batteries as a high-technology, energy-intensive sector, and outdoor clothing as a consumer-goods industry characterised by low unit value and high logistics intensity. By integrating multi-objective optimization with agent-based simulation and dynamic risk modelling, the research examined how production location, sourcing strategy, and demand allocation interact when tariffs, carbon emissions, and service levels are jointly considered. Despite the structural differences between the two industries, the results converge toward a consistent and robust strategic conclusion. In both case studies, production strategies that allocate a substantial share of manufacturing capacity close to other supply chain actors, systematically outperform alternatives relying on Chinese manufacturing sites. Under an equal-tariff regime, the traditional cost advantages associated with China, such as low labour, energy, and land costs, are largely offset by high tariffs applied to both raw materials and finished goods. Further analysis of alternative configurations reinforces this finding. European-based solutions, especially in the power batteries case, offer environmental advantages due to lower electricity carbon emission factors but incur high production and tariff costs that significantly reduce their economic attractiveness. Third-country solutions in Latin America for the high-tech industry partially mitigate tariff exposure; however, they remain disadvantaged by long supply routes and limited proximity to final demand. Despite these constraints, such configurations remain cost-competitive, as production-related costs in the United States do not sufficiently outperform them. In contrast, in the consumer goods industry, configurations that concentrate a large share of production in the United States combine tariff avoidance, proximity to the end market, and higher service reliability. As a result, these configurations emerge as the most balanced and robust solutions, given the high impact of transportation costs and tariff burdens on economic supply chain performance.

Overall, proximity plays a crucial role in contemporary supply chains. While the optimal configuration varies by industry, this study demonstrates that actors in at least two echelons must be geographically close to each other to outweigh the production and land-cost advantages historically offered by Chinese manufacturing sites, which previously shaped offshoring strategies.

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