Mixed-Integer Multi-objective Programming for Intermodal Supply Chain Design

Marco Marto[1(✉)], Valentina Chkoniya[1,2], Eduardo B. Couto[3], Telmo Pinto[4], Marco S. Reis[5], and Agostinho Agra[6]

[1] Aveiro Institute of Accounting and Administration, University of Aveiro, 3810-500 Aveiro, Portugal
{marcovmarto,valentina.chkoniya}@ua.pt
[2] GOVCOPP - Research Unit in Governance, Competitiveness and Public Policies, University of Aveiro, 3810-193 Aveiro, Portugal
[3] Department of Economics, Management, Industrial Engineering and Tourism, University of Aveiro, 3810-193 Aveiro, Portugal
belmiro@ua.pt
[4] Centre for Mechanical Engineering, Materials and Processes, ARISE, University of Coimbra, 3004-531 Coimbra, Portugal
telmo.pinto@dem.uc.pt
[5] CERES, Department of Chemical Engineering, University of Coimbra, 3030-790 Coimbra, Portugal
marco@eq.uc.pt
[6] Department of Mathematics and CIDMA - Center for Research and Development in Mathematics and Applications, University of Aveiro, 3810-193 Aveiro, Portugal
aagra@ua.pt

Abstract. In recent years, the occurrence of some political events around the world, some diseases (e.g. Covid-19) and severe weather events have led decision-makers to consider more about the uncertainty and disruption of the routes available for the distribution of some important agricultural products such as soybeans and corn. This work aims to study some advantageous Supply Chain Networks Design (SCND) for the distribution of soybeans and corn considering the uncertainty in supply, demand and transportation costs on intermodal routes for the distribution of soybeans and corn in Europe and North Africa. The objectives considered are to minimize the costs associated with transportation and distribution, and to consider environmentally friendly solutions as soon as possible, taking into account the carbon footprint (green solutions). Starting from a deterministic model, uncertainty is introduced by considering a set of scenarios, and then the multi-objective version of the model is considered, taking into account the economic and environmental objective functions. The solutions emphasize the strategic positions of the ports of Itaqui, and New Orleans as supply ports, and Sines, Lisbon, Gijon, Tarragona, Casablanca, and Antwerp as distribution (transshipment) ports in the design of the networks according to the objectives. The advantageous position of Port of Sines is analyzed and discussed according to the aims of this work of building intermodal Supply Chain Networks.

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1 Introduction

This study focuses on the supply chain for soybeans and corn, mainly to be distributed to meet demand from Europe and North Africa.

Soybeans and corn are essential commodities in the food chain of Europe and North Africa not only to produce final consumer products, but also to raise livestock for human consumption [1–3]. European and North African countries are increasingly dependent on the cheaper and more productive land of South America to provide sufficient quantities of these products.

Demand for both commodities is seasonal (12 months) and prices (per ton) are strongly correlated. The price (per ton) of soybeans is more than 2 times higher than the price (per ton) of corn [4,5].

Since the beginning of the current century, soybean supply chains have been shifting towards South American countries (e.g. Brazil, Argentina) as the main suppliers, instead of North American suppliers (e.g. U.S.A, Canada). Corn supply chains are shifting in the same direction, but more slowly, so that South America will soon be the continent's main supplier [6].

Supply chains do not just change for economic reasons, they can also change for political reasons, environmental and social reasons and, possibly, natural disasters. They need to be flexible, easily adaptable and intermodal (using the sea, roads and railways, for example) to deal with any disruptions that may occur (e.g. political reasons; [7]). Intramodality is also important due to concerns about global warming and to reduce gas emissions [8]. Increasingly, government bodies are more concerned and have targets to meet with regard to gas emissions.

We must therefore add environmental objectives when we think about the food supply chain. Supply chains that take environmental objectives into account are sometimes referred to as green supply chains [9].

Considering the trend of the main suppliers moving from North to South America and the economic and environmental concerns in the design of supply chains, Port of Sines is seen as one of the main candidates for the supply of soy and corn, mainly to the Mediterranean countries and, eventually, as a transshipment port for the traditional North Sea ports [10].

The strategic advantages of Port of Sines [11] are illustrated in this study with an intermodal supply chain network design (SCND) deterministic model, which is run on some realistic scenarios to deal with route uncertainty and to better propose alternatives in case of route disruptions.

Previous studies have considered SCND models to supply commodities in countries or regions. Jia et al. [12], reviewed articles on soy supply chain management and sustainability. The term sustainability is often associated with economic, social and environmental objectives or goals. They mainly analyzed four themes: land use policies; value chain governance; CO_2 emissions reduction and barriers, for example, related to demand. A conceptual model was proposed.

Nadery et al. [13] developed a Benders decomposition approach in an SCND optimization to model wheat distribution in Iran. Previously, Bidhandi et al. [14] proposed a mathematical programming formulation and algorithms dedicated to deterministic, multi-commodity and single-period SCND models, where a modified version of the Benders decomposition is proposed. Wang et al. [9] introduced a multi-objective green SCND model interested in the trade-off between total cost and environmental influence for strategic company planning. The term "green" in supply chain models is often associated with environmental concerns, objectives or targets.

To design this type of supply chain, it is sometimes important to take into account uncertainties, for example in supply, demand and transportation costs. In these cases, sometimes stochastic programming techniques are used to model uncertainty, usually after constructing a set of realistic scenarios [15].

The main objective of this study is to build an economically and environmentally optimized supply chain network to distribute soy and corn enough to satisfy the demand in Europe and North Africa under eight realistic scenarios, considering the South American continent as the main source of these commodities. As expected, the results show the possible relevant role of Port of Sines as one of the main distribution centers (transshipment ports) in this SCND. This study may help to justify the opening of a grain terminal in Port of Sines.

The present study is divided into four main sections: Introduction, Materials and Methods, Results, and Discussion and Conclusion. After the presentation, context and objective of the study in the Introduction, the Materials and Methods section presents the scenarios used and their sources, the parameters and indices used in the modeling task, the decision variables used, the two objective functions and the constraints. It follows the Results section that presents and analyzes the main results that are last discussed and help us to emphasize the relevant position of port of Sines in this study in the Discussion and Conclusion section.

2 Materials and Methods

The SCND model was developed with two objectives: to minimize routing related costs and to minimize CO_2 equivalent emissions in transportation (Green Bi-objective Mixed Integer Linear Programming Model).

Based on the historical demands for soybeans and corn in Europe and North Africa available in the FAOSTAT 2024 [16] databases and using Holt's additive forecasting model, the demands for the year 2024 were estimated according to the proportion of individual demands for the last known year. The averages of the monthly prices of soybeans and corn [4,5] were used to estimate the countries' demands for all twelve months of 2024. As well as being a multi-period model, it does not accumulate commodity stocks for future periods due to the perishability of commodities.

First, we present the scenarios. Then we present the deterministic model, its parameters, its decision variables, its objective functions and its constraints.

It is assumed that all demand is satisfied, although depending on the scenario, the proportion of supply required is limited to a specific port of origin in North or South America, depending on the proportion of commodity production. The tons of soybeans and corn that arrive at the distribution centers are processed (cleaned, dried, fumigated) and, in the case of soybeans, a portion is converted to meal at the transshipment ports. This results in a loss of production and a resulting transformed product, along with a portion of the remaining untransformed commodity.

2.1 Scenarios

The set of eight scenarios in Table 1 was used to adjust the parameters of the model according to some types of uncertainty in the supply chain market, supply and demand for soybeans and corn, as well as possibilities of (extreme) price changes for some modes of transportation.

Table 1. Scenarios used to change some parameters and run the model.

Scen. Nr.	Supply Prop. from North America - Soya	Supply Prop. from South America - Soya	Supply Prop. from North America - Corn	Supply Prop. from South America - Corn	Perc. Variation for Demand of Soya	Perc. Variation for Demand of Corn	Perc. Variation for Transp. Costs in Roads	Perc. Variation for Transp. Costs in Rails	Perc. Variation for Transp. Costs in Sea
1	41.00%	59.00%	77.29%	22.71%	3.87%	5.49%	4.11%	2.10%	17.50%
2	41.00%	59.00%	77.29%	22.71%	3.87%	5.49%	4.11%	2.10%	0.00%
3	34.98%	65.02%	69.11%	30.89%	0.00%	0.00%	0.00%	0.00%	0.00%
4	34.98%	65.02%	69.11%	30.89%	0.00%	0.00%	0.00%	bigM	0.00%
5	34.98%	65.02%	69.11%	30.89%	0.00%	0.00%	bigM	bigM	0.00%
6	47.40%	52.60%	85.64%	14.36%	0.00%	0.00%	0.00%	0.00%	0.00%
7	47.40%	52.60%	85.64%	14.36%	0.00%	0.00%	0.00%	bigM	0.00%
8	47.40%	52.60%	85.64%	14.36%	0.00%	0.00%	bigM	bigM	0.00%

The first column is the number of scenarios. The second through fifth columns represent the maximum share of total commodity demand that can be met by North or South American ports based on the historical variation of production proportions [17] in North (e.g., USA, Canada, Mexico) and South America (e.g., Brazil, Argentina, Paraguay) from 2004/2005 to 2023/2024. The scenarios change according to the minimum, average, and maximum proportions of production of these commodities in North and South America [17] over this historical period of twenty years. The sixth and seventh columns represent the percentage changes in commodity demand based on Mordor Intelligence reports [18–20] or no change, which means 0.00%. The eighth to tenth columns represent the percentage change in transportation costs (sea, road and rail) based on Mordor Intelligence reports and the ERSE (Portuguese Energy Services Agency) proposal to increase electricity prices or no change meaning 0.00%. Note that when the value bigM appears, represents an extremely high percentage increase to avoid that mode of transportation.

2.2 Parameters and Indices

The following parameters and indices are used in the bi-objective deterministic model:

- n is the number of suppliers (ports of origin) $i = \{1, 2, .., n\}$;
- b is the number of distribution centers (transshipment/intermodal points) $k = \{1, 2, ..., b\}$;
- m is the number of countries of destination $j = \{1, 2, ..., m\}$;
- ht is the number of months, $t = \{1, 2, ..., ht\}$;
- v_{jk} is the number of combinations of transportation modes for distribution center k and destination j (e.g. (sea, roads),(sea, rails),(sea, rails, roads)) $l_{jk} = \{1, 2, ..., v_{jk}\}$;
- np is the number of products $p = \{1, ..., np\}$;
- d_{jp}^{t} is the destination country j demand (Ktons) of product p to month t;
- f_{kp} is the fixed cost of distribution center k for product p;
- $st_{jkl_{jk}p}$ is the fixed cost of transport mode combination l_{jk} for product p from distribution center k to destination j;
- g_{ip}^{t} is the supplier i capacity of product p for month t in Ktons;
- e_{kp}^{t} is the distribution center (transshipment port) k capacity (Ktons) for product p for month t;
- c_{ikp} is the unit cost (EUR/Ktons) of transportation between supplier i and distribution center k for product p;
- $r_{jkpl_{jk}}$ is the unit cost (EUR/Ktons) of combination of transportation mode l_{jk} between distribution center k and destination j for product p;
- fc_k is the cost (EUR/Ktons) for using a distribution center k;
- fsc_i is the fixed cost (EUR) for using a supply port i;
- α_{ip} is the proportion of product p from supplier i to be transformed;
- β_{ip} is the useful transformed proportion of product p from supplier i;
- ex_{ik} is the CO_2 equivalent emissions in tons/Ktons for transportation from origin i to distribution center k;
- $ey_{jkl_{jk}}$ is the CO_2 equivalent emissions in tons/Ktons for transportation from distribution center k to destination j using transport mode combination l_{jk};

The objective is to meet the demand of destination countries (j) from origin ports (i) (suppliers in North and South America) while respecting the capacity constraints of the origin ports (i). Terminals in European or North African ports have distribution centers (transshipment ports) that can receive goods by sea from origin ports. If necessary, these centers can also process, fumigate, and dry perishable goods. Then, commodities (corn and soybeans) are delivered to the destination countries via the shortest route using combinations of transportation modes l_{jk}, taking into account various alternative intermodal routes by sea, road, or rail.

2.3 Decision Variables

The mixed integer programming model includes the following decision variables:

$$X_{ikp}^{t} = \begin{cases} 1, & \text{if supplier } i \text{ is serving distribution center } k \text{ for product } p \text{ and month } t \\ 0, & \text{otherwise} \end{cases},$$

$Y_{jkl_{jk}p}^{t}$ – continuous variable for the proportion of the destination country j demand distributed with transport mode combination l_{jk} by distribution center k for product p and month t,

$$Z_{kp}^{t} = \begin{cases} 1, & \text{if distribution center } k \text{ is opened for product } p \text{ and month } t \\ 0, & \text{otherwise} \end{cases},$$

$$W_{jkl_{jk}p}^{t} = \begin{cases} 1, & \text{if transport mode combination } l_{jk} \text{ is used to distribute product } p \\ & \quad \text{from distribution center } k \text{ to destination } j \text{ in month } t \\ 0, & \text{otherwise} \end{cases},$$

H_{ikp}^{t} – continuous variable for the flow from supplier i to distribution center k for product p and month t (in Ktons)

2.4 Objective Functions

This work uses multi-objective lexicographic optimization [20]. A higher priority is given to minimizing the routing cost function and a lower priority to minimizing CO_2 equivalent emissions when routing supply sources to demand points in Europe and North Africa. The following objective function minimizes the costs in the supply chain network.

$$\begin{aligned} \text{Min} \quad & \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{k=1}^{b} f_{kp} Z_{kp}^{t} + \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{i=1}^{n}\sum_{k=1}^{b} c_{ikp} H_{ikp}^{t} \\ & + \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{k=1}^{b}\sum_{j=1}^{m}\sum_{l_{jk}=1}^{v_{jk}} r_{jkpl_{jk}} d_{jp}^{t} Y_{jkl_{jk}p}^{t} + \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{k=1}^{b}\sum_{j=1}^{m}\sum_{l_{jk}=1}^{v_{jk}} st_{jkl_{jk}p} d_{jp}^{t} W_{jkl_{jk}p}^{t} \\ & + \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{i=1}^{n}\sum_{k=1}^{b} fc_{k} H_{ikp}^{t} + fsc_{i} X_{ikp}^{t} \end{aligned} \tag{1}$$

The objective function below minimizes the CO_2 equivalent emissions in the supply chain network.

$$\text{Min} \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{i=1}^{n}\sum_{k=1}^{b} ex_{ik} H_{ikp}^{t} + \sum_{t=1}^{ht}\sum_{p=1}^{np}\sum_{k=1}^{b}\sum_{j=1}^{m}\sum_{l_{jk}=1}^{v_{jk}} ey_{jkl_{jk}} d_{jp}^{t} Y_{jkl_{jk}p}^{t} \tag{2}$$

2.5 Constraints

In this section, the constraints of the deterministic model are introduced.

$$\sum_{k=1}^{b}\sum_{l_{jk}=1}^{v_{jk}} Y^t_{jkl_{jk}p} = 1 \ ,\forall j,p,t \tag{3}$$

$$\sum_{j=1}^{m}\sum_{l_{jk}=1}^{v_{jk}} d^t_{jp} Y^t_{jkl_{jk}p} \leq e^t_{kp} Z^t_{kp} \ ,\forall k,p,t \tag{4}$$

$$\sum_{j=1}^{m}\sum_{l_{jk}=1}^{v_{jk}} d^t_{jp} Y^t_{jkl_{jk}p} \leq \sum_{i=1}^{n}\{(1-\alpha_{ip})+\alpha_{ip}\beta_{ip}\} H^t_{ikp} \ ,\forall k,p,t \tag{5}$$

$$H^t_{ikp} \leq g^t_{ip} X^t_{ikp} \ ,\forall i,k,p,t \tag{6}$$

$$Y^t_{jkl_{jk}p} \leq W^t_{jkl_{jk}p} \ ,\forall j,k,l_{jk},p,t \tag{7}$$

$$W^t_{jkl_{jk}p} \leq Z^t_{kp} \ ,\forall j,k,l_{jk},p,t \tag{8}$$

$$X^t_{ikp} \in \{0,1\} \ ,\forall i,k,p,t; Y^t_{jkl_{jk}p} \in [0,1] \ ,\forall j,k,l_{jk},p,t; Z^t_{kp} \in \{0,1\} \ ,\forall k,p,t;$$
$$W^t_{jkl_{jk}p} \in \{0,1\} \ ,\forall j,k,l_{jk},p,t; H^t_{ikp} \geq 0 \ ,\forall i,k,p,t \tag{9}$$

Constraints (Eq. 3) ensure that the destination country's demand is fully satisfied by distribution centers and mode combinations for all products and months. Each country's demand for each product and month is satisfied by one or more distribution centers (transshipment ports). The constraints (Eq. 4), (Eq. 5) and (Eq. 6) guarantee that the capacities of the distribution centers and suppliers are not exceeded and that the demand in the countries is satisfied. (Eq. 4) means that the sum of demand from all countries coming from each distribution center for each product and for each period does not exceed its capacity. (Eq. 5) means that the sum of the demand from all countries, for all products and months, does not exceed the flow of the product that arrives at the distribution center from the supplier's port after the transformation process in the case of soybeans. (Eq. 6) means that the capacity of the supplier ports is not exceeded for all products and months. An origin can serve one or more distribution centers for each product and month. Constraints (Eq. 7) and (Eq. 8) assign a mode combination for each route from distribution center and destination country, if the route is used and if the distribution center is open, for all products and months. (Eq. 9) represent the supports of the decision variables.

3 Results

The scenarios constructed for the SCND problem of soybean and corn distribution in Europe and North Africa were run for the bi-objective deterministic model in the gurobi optimizer (version 11.0.3) in Python and resulted in eight solutions (one per scenario, with the same routes across all months), but some

of them represent similar routes (Figs. 1, 2, 3, 4, 5, 6 and Fig. 7). A PC with 16 GB of RAM and a 3.20 GHz processor was used. All code was written in Python using the following libraries: networkx, geopandas, gurobipy, searoute and routingpy.

Most of them are based on the supply port of Itaqui with the transshipment or distribution ports of Sines and Lisbon, but also the ports of Gijon, Le Havre, Casablanca, Tarragona, Hamburg, Antwerp and Rotterdam (scenarios 1, 2, 3, 4, 5, 6 and 7). In these scenarios, the distribution of the two commodities is distributed among the different transshipment ports and always has the advantageous origin position of the port of Itaqui. On the other hand, if the use of rail and road is considered too expensive and the capacities of the South American ports are the lowest of all the scenarios (Scenario 8), the model selects the Port of Itaqui and the Port of New Orleans as supply ports and more or less the same set of distribution ports. Scenario 8 is slightly more favorable for distribution ports in Northern Europe to supply corn.

Both commodities flow from origin ports in the Americas to transshipment distribution ports in Europe and North Africa. In the case of soybeans, with the exception of soybeans from the port of Buenos Aires (which arrive already transformed), there is a process of transformation of a portion into meal at the transshipment ports (distribution centers). In the transshipment ports, there are some costs associated with cleaning, drying and fumigation operations, if necessary. The most common (and important) distribution centers in all scenarios are

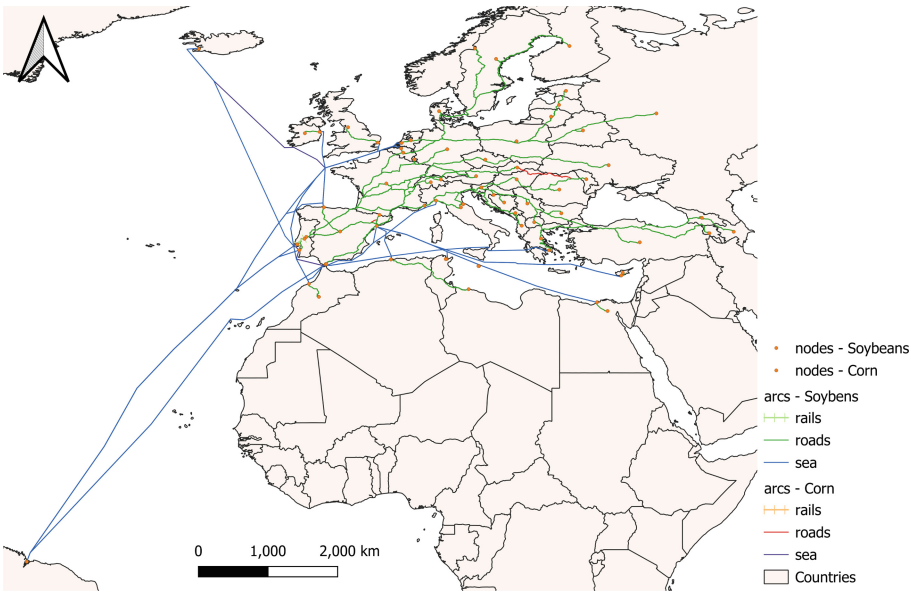

Fig. 1. Scenario 1 and scenario 2 (routes are very similar) from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

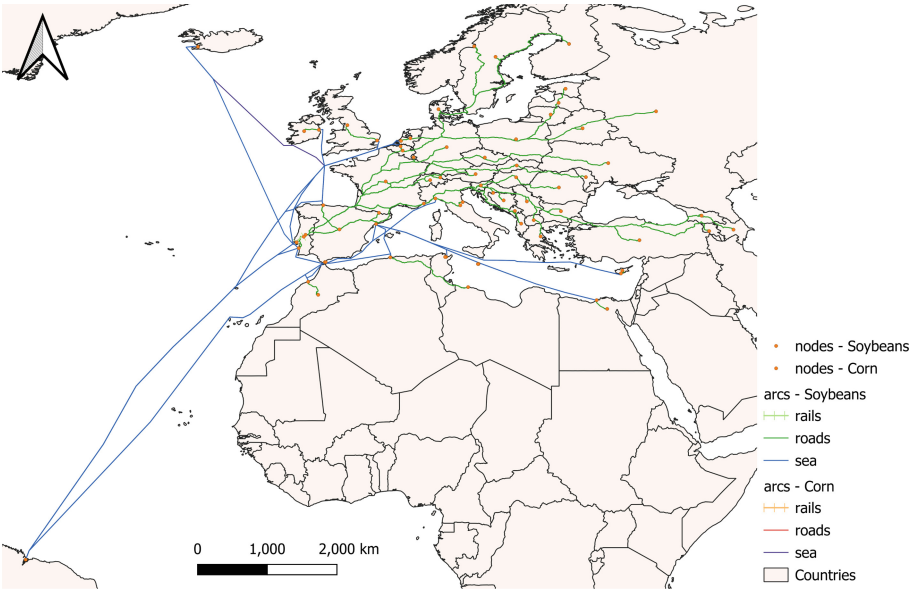

Fig. 2. Scenario 3 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

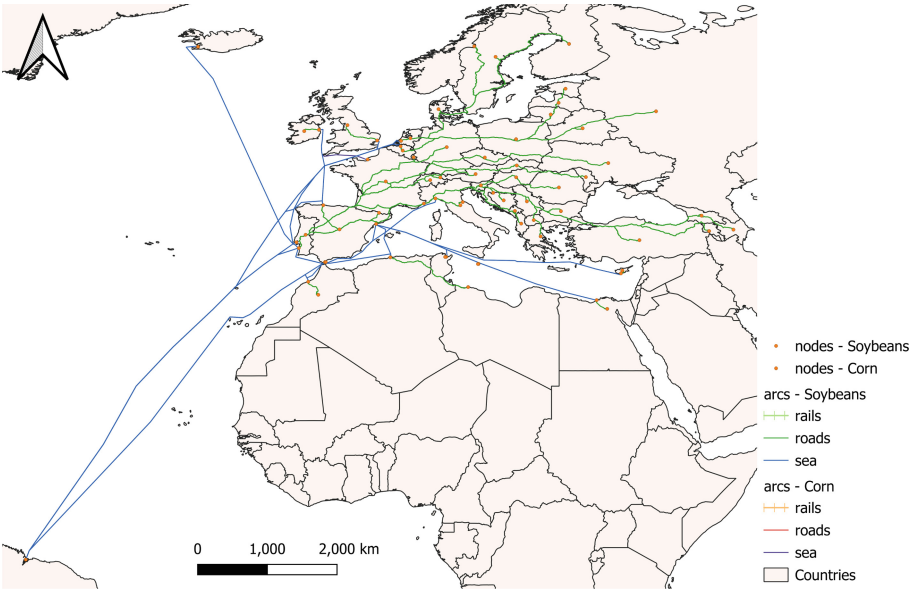

Fig. 3. Scenario 4 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

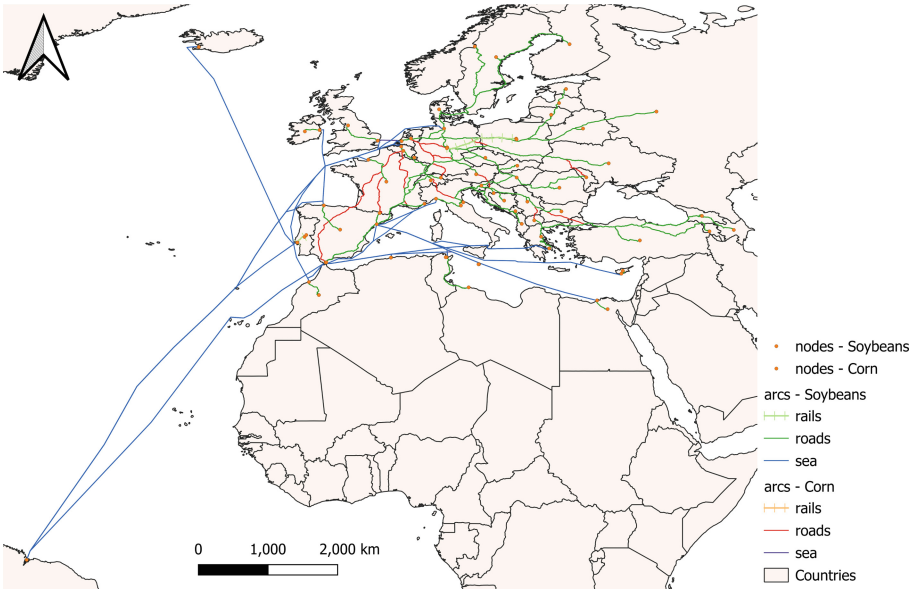

Fig. 4. Scenario 5 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

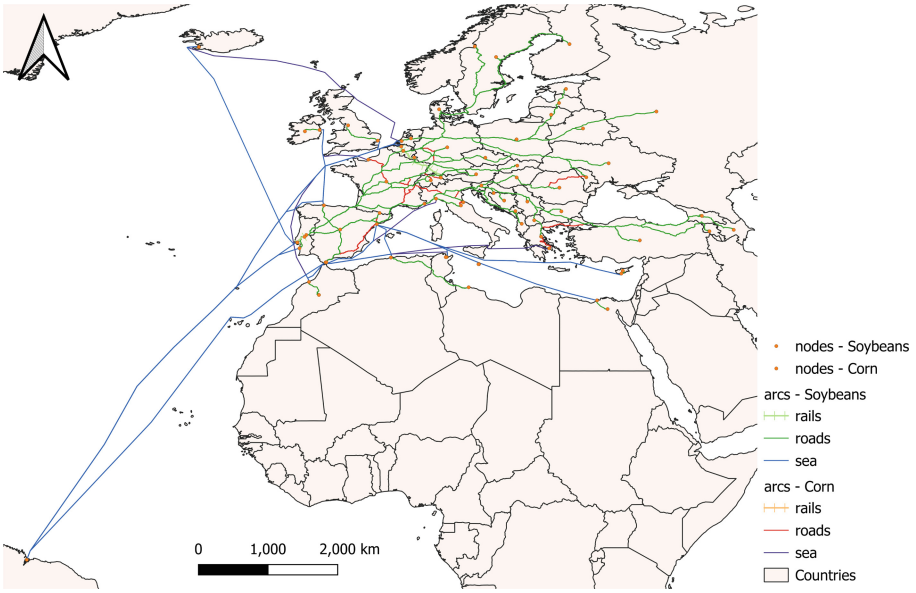

Fig. 5. Scenario 6 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

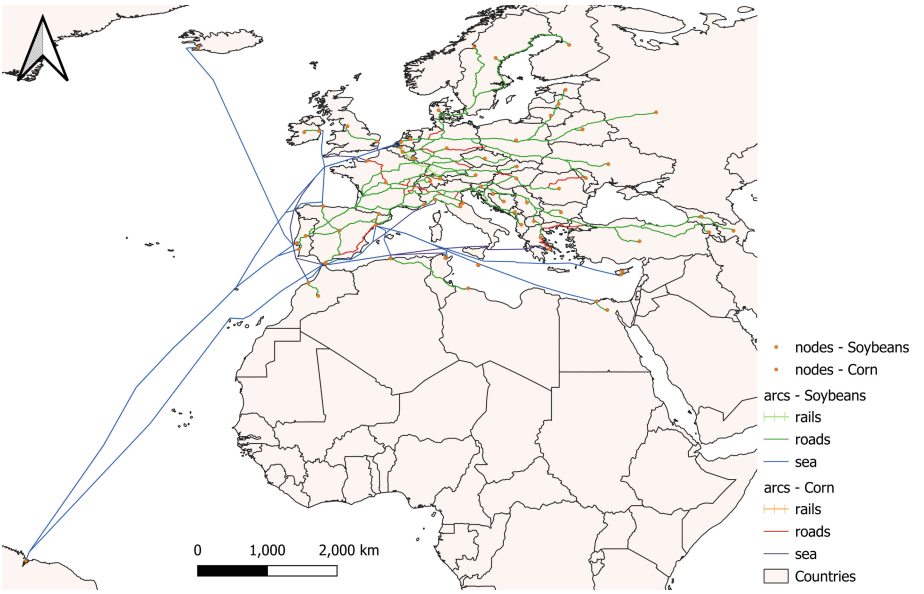

Fig. 6. Scenario 7 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

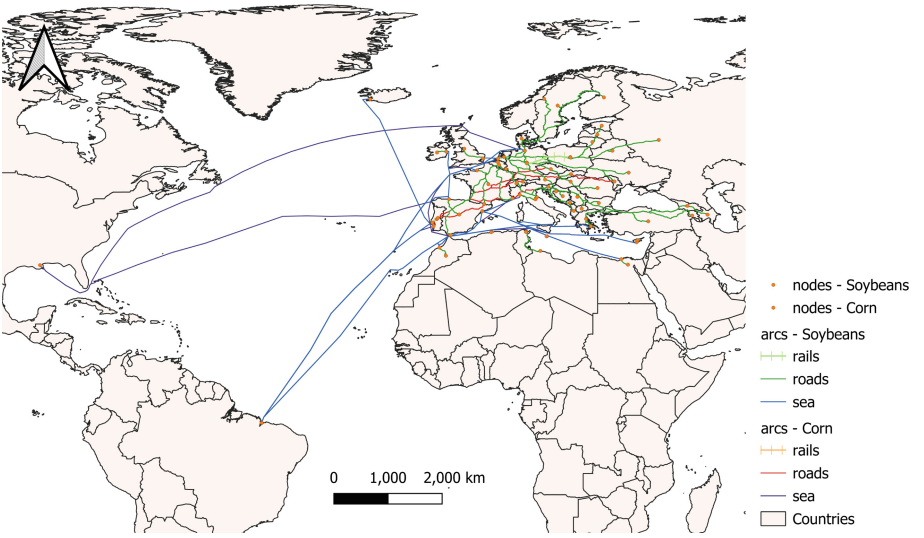

Fig. 7. Scenario 8 from month 1 (January) to month 12 (December). Deterministic model routing solutions for scenarios 1 to 8.

Port of Sines, Port of Lisbon, Port of Antwerp, Port of Gijon, Port of Tarragona, and Port of Casablanca.

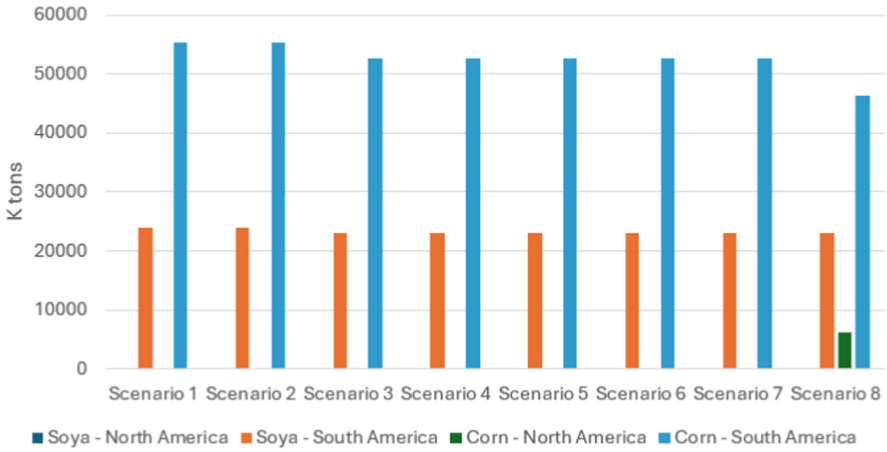

Fig. 8. Annual flow of commodities (soya and corn) from America to Europe and North of Africa for each scenario.

Figure 8 summarize the annual (sum of all months) commodity flows from the Americas to Europe and North Africa. The flows of both commodities from ports in America are the same in scenarios 1 and 2 (about 24,000 Ktons soy and 55,000 Ktons corn), slightly higher than the values for the other scenarios (about 23,000 Ktons soy and 52,500 Ktons corn), because scenarios 1 and 2 take into account the percentage increase in demand for both commodities.

The distribution of soybeans for all scenarios flows through the port of Itaqui (South America), which mainly reflects the effect of the cheapest origin of the commodities. The distribution of corn flows is more sensitive to the higher costs of both land transport modes (rail and road), partly due to the higher volumes that need to be transported compared to the volumes of soybeans. In Scenario 8, some flow of corn from North America is obtained to meet the required demand due to the lowest proportion of supply imposed on the South American port by this scenario (14%) and the comparatively favorable cost of transporting commodities by sea. Scenario 8 shows a higher flow of corn from North America compared to the other scenarios (with favorable ocean transportation costs), in part because the proportion of corn supply from the North American port is about 86% (the highest proportion of all scenarios).

In general, the main (and cheapest) shipping ports for soy and corn are in South America (namely the port of Itaqui), but it is useful to have several scenarios in case of route disruptions in the usual SCND.

4 Discussion and Conclusion

This work may justify the need for a strategic port in Southern Europe or North Africa to serve the demand for soy and corn in Europe and North Africa as a better alternative to the traditional North Sea ports in Northern Europe.

Soybean and corn production is shifting from North America to South America in this century.

Agricultural land in South America (e.g. Brazil, Argentina) is cheap and very productive, making it attractive for agro-industries related to the production of soy and corn. In this exercise, this trend can be seen in the soy supply chain and in the corn supply chain (Fig. 8), although the main corn producing region is still North America (USA).

Therefore, the main supply port for soy and corn is the port of Itaqui (South America, and in some cases the port of New Orleans), and the lower costs and CO_2 equivalent emissions associated with the transportation of commodities indicate that the main distribution center ports for Europe and North Africa are mainly port of Sines, but also the port of Lisbon, the port of Le Havre, the port of Casablanca, the port of Tarragona, the port of Gijon, the port of Hamburg, the port of Antwerp and the port of Rotterdam, depending on the scenario used.

Most scenarios show port of Sines as one of the main ports for supplying soy and corn to all of Europe and North Africa. The port of Sines has more favorable natural and strategic characteristics (e.g. deep water terminals, more functional) compared to the other candidates. Analyzing and comparing the routes from the transshipment port of Lisbon with the transshipment port of Sines to the destination countries, it can be observed that the main difference is the use of a segment of transportation by rail between Lisbon and the distribution point in Portugal.

The rail network used in this work allows intermodal transportation, but at the time of this work it was not the most recent and of poor quality. Fortunately, the more recent version of RNE would select port of Sines as the transshipment port more often in most scenarios, which would directly impact the available combinations of transportation modes and associated costs. The RNE rail network is being integrated into the intermodal network of this study at the time of writing.

Moreover, considering the commodity flows (more than 23,000 Ktons of soybean and 52,500 Ktons of corn), it is easy to justify the advantageous strategic (Moreira, 2015) position of port of Sines in the SCND of grains in Europe and North Africa.

This model can be used as a logistics optimization tool. It helps determine the optimal path based on logistics destinations and known constraints. The goal is to optimize overall costs and emissions, which includes time to market, vessel allocation, and capital implicitly.

It provides decision-makers with information on selecting logistics routes and transportation methods. It helps model transportation networks with various paths, identify the most efficient route, and ensure the effective transportation of goods using various combinations of transportation modes and vehicles that serve multiple hubs, ports, and destinations.

Future work will focus on stochastic and robust versions of the model, which are advantageous approaches for this study because they can take into account different sources of uncertainty (e.g. demand, supply, costs).

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