Cost and Carbon Implications of a Patient-Centric Supply Chain

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ABSTRACT

Trends toward patient-centric deliveries in the pharmaceutical industry pose a challenge for integration of sustainable supply chain design. This patient-centricity entails more distributed demand, smaller shipments, and more frequent deliveries. Our research utilizes scenario planning for quantification of CO_2e and taxation within a pharmaceutical distribution network located in Brazil, where tax policy has a major impact on supply chain costs. Comparison between various scenarios allows for analysis of the taxation and CO_2e emissions variations, with results showing how the patient-centric scenario is associated with increased CO_2e emissions, and how taxation is not directly impacted by patient-centricity. Despite this, taxation does have a major effect on decision making for the location of distribution centers in Brazil. A scenario assessing the consolidation of demand at a weighted center-of-gravity (CoG) distribution center resulted in an estimated 10.1% savings on tax and 23.4% of CO_2e reduction when compared to the base case scenario.

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CHAPTER 1: INTRODUCTION

Awareness of climate change and its impact on human health is driving societal and behavioral shifts to more sustainable business practices (World Health Organization, n.d.). Despite this focus on sustainability, recent consumer behavior has increased the demand for carbon-intensive at-home deliveries. Growing at-home demand has pushed supply chains across various industries to develop or revamp their direct-to-consumer distribution channels. In the pharmaceutical industry, direct-to-consumer distribution channels are highly patient-centric. Patient-centricity ensures the delivery process meets the unique needs of individual patients such as delivery close to the patient's location and preferred delivery time (Srivastava, 2022). When assessing these personalized distribution networks, many obstacles complicate a corporation's ability to gauge the tradeoff between transportation costs and carbon emissions.

1.1 Motivation

The focus on human health and sustainability is core to the mission at Roche AG, a Swiss pharmaceutical company with distribution across 95 countries. Roche was founded in 1896, and since their founding, the corporate mission has concentrated on patient-centric healthcare solutions. While Roche currently has a very mature product mix with oncology treatments contributing to the majority of revenues, it also has a robust pipeline of new products being developed to align with the corporate mission of "Doing now what patients need next." (Roche, 2023).

Roche's pipeline of new patient-centric products paired with changing industry dynamics has led them to reevaluate their distribution network in Brazil. Roche distributes and accounts for product sales in Brazil under three main divisions: diabetes, diagnostics, and pharmaceuticals.

Across these three divisions, there are multiple distribution centers and offices. The current

distribution network is optimized for cost with an emphasis on tax-compliance considerations.

Any new distribution model must account for increases in patient-centric new-product

introductions without losing sight of the complexities of the Brazilian tax system and the overall

cost to serve the patient. At the same time, Roche considers it a priority to reduce its carbon

footprint in Brazil and therefore must be able to evaluate carbon emissions that would be

generated by a new distribution model. Ultimately, the company wants to ensure that patients are

continually served by an efficient, sustainable, and financially viable supply chain. As described

in Sections 1.1.1 and 1.1.2, Brazil's regulatory system for pharmaceuticals and complex taxation

system make this a difficult objective to achieve.

1.1.1 Regulatory Environment in Brazil

Pharmaceuticals in Brazil are regulated by a regulatory body called Anvisa. Anvisa is

comparable to the Food and Drug Administration (FDA) in the United States (US). A

comparison of regulatory approval of oncology products between the US and Brazil

demonstrated an 8.6-month delay for Anvisa in contrast to the FDA approval process

(Bustamante et al., 2015). In addition to the delays, Anvisa seems to have a poor relationship

with the players in the pharmaceutical industry, as evidenced by a survey that found industry

players complaining that they operate in South American markets but would rather not enter the

Brazilian market because "It's too complicated" (Limoeiro 2019). The current market is difficult

to enter and complying with regulations is a major cost for companies.

Pharmaceutical companies are motivated to prepare for the distribution of a drug as soon as

regulatory approval is granted due to the short window for capitalizing on a patent before

expiration. Therefore, Roche can benefit from the ability to evaluate potential supply chain scenarios that may arise in the future. However, the task of planning for these scenarios is complicated by the intricate tax policies in Brazil.

1.1.2 Brazilian Taxation System

Within Brazil, there are twenty-six states, each with different incentives and regulations on how taxes are imposed on logistical activities. Brazil has one of the most complex tax structures in the world, and any new products will need to account for tax impacts imposed on distribution costs. For this reason, pharmaceutical industry participants in Brazil have traditionally consolidated their operations in favorable tax havens, such as the Goias region. Specifically, two of the largest Brazilian drug manufacturers, Teuto and Neoquimica, as well as Roche all have located operations in this region (Limoeiro, 2019; Roche, 2023). Taxes in Brazil include a multitude of state, federal and municipal rates, and the pharmaceutical industry specifically has unique "Convenios" agreements that can adjust tax rates based on specific product end uses. For example, Convenio 87 results in an exemption for certain pharmaceutical products from the State Value Added Tax (VAT) rate (Roche, 2022).

The most relevant tax to supply chain operations in Brazil is the VAT rates which cover the transportation of products in Brazil and vary by state. In Brazil, state VAT is called ICMS. ICMS is the state specific indirect taxation on the circulation of merchandise, even when the transaction and the rendering of services start in another country (PricewaterhouseCoopers, 2022).

1.2 Problem Statement

Sustainable supply chain network design depends in large part on reducing the CO_2e (carbon dioxide equivalent) emissions associated with the transportation of goods. As noted in Section

1.1, in addition to considering carbon emissions, a network design for Roche's future patient-centric new products in Brazil must also account for exogenous factors such as taxation that have a substantial impact on the cost of distribution to the patient.

However, modeling the proposed network for Roche will not involve conducting traditional optimization techniques to minimize the total cost or CO_2e involved in distribution. Instead, we will model various supply chain scenarios, assessing how they may differ from status quo distribution methods in impact on total carbon emissions and taxation. All analysis conducted is based on utilizing data for diabetes and pharmaceutical divisions, with no diagnostics data being used. The diagnostics division includes equipment sales, maintenance, and service of placed equipment. These confounding variables required additional data cleaning of the diagnostics datasets, following discussions with Roche management, the diagnostics division was not included in the research.

1.2.1 Research Questions

Our model will be structured to answer the following questions:

1. What is the tradeoff between carbon emissions and taxation within the transportation network?

2. How do new product introductions (NPI) influence the way products may be distributed?

3. How does increasing patient-centric distribution influence CO_2e emissions and taxation?

1.3 Hypotheses

We hypothesize that patient-centric distribution is positively correlated with increased CO_2e emissions. To validate this hypothesis, the above questions are modeled in the supply chain utilizing various scenario-planning models. Outputs of the models are compared with the status quo, allowing for a comparison of the taxation and CO_2e between scenarios.

1.3.1 Selected Scenarios

Modeling is extrapolated from nine months of product demand, January to September 2022, with the following scenarios tailored to answer the research questions outlined in Section 1.2.1:

1. **Base Case Scenario(s):** The status quo data is run through the model to establish two control groups, pharmaceutical division control and diabetes division control.

    i. **Pharmaceutical division control:** Pharmaceutical products are being distributed from one current distribution center located in the state of Goias.

    ii. **Diabetes division control:** Diabetes products are being distributed from one current distribution center located in the state of Santa Catarina.

2. **Consolidation Scenario:** Pharmaceutical and diabetes division demand are consolidated under one new hypothetical distribution center, located in Minas Gerais (Location of Minas Gerais decided using Center-of-Gravity analysis). This scenario is contrasted with the pharmaceutical and diabetes division control groups to answer Research Question 1, identifying the tradeoff of CO_2e emissions and taxation within the transportation network.

3. **Patient-Centricity Scenario:** Patient-centricity modeling is compared with the data from the pharmaceutical division control group, utilizing the pharmaceutical distribution

center. This scenario has two components: modeling new product introductions, and assessing the tradeoff associated with increasing patient-centricity.

i. **New product introductions:** To assess Research Question 2 of how new product introductions influence the way products may be distributed, new product introductions are modeled utilizing adjustments to existing product demand. Additionally, this scenario allows for the modeling of new customer demand nodes in cities that have not been shipped to before.

ii. **Tradeoff associated with increasing patient-centricity:** To assess Research Question 3 of how increasing patient-centricity may impact the tradeoff of CO_2e emissions and taxation within the network, a modal shift input variable is introduced into the model. Modal shift from road to air allows for the modeling of shorter lead time of product distribution, as relevant to patient-centricity through discussion in Section 2.3.

CHAPTER 2: STATE OF THE ART

The research conducted to contextualize the creation of a model starts with the quantification of CO_2e emissions. Section 2.1 outlines the CO_2e calculation methodology, and Section 2.1.1 delves into how utilization of vehicles may impact CO_2e emissions. Next, Center-of-Gravity analysis (CoG) is explored as a methodology to identify alternative locations for distribution center(s). The CoG calculations and visualization of the data are discussed in Section 2.2. Section 2.3 contains research on patient-centricity and what metrics align with pharmaceutical industry interpretations of patient-centricity.

Our assessment of current academic literature did not find other models that are working with taxation and CO_2e in the context of a patient-centric supply chain. Despite this, individual components of our modeling are discussed in research publications. Therefore, Section 2.4 analyzes modeling taxation within Brazil. Section 2.5 contains an understanding of literature on the tradeoff between freight cost and CO_2e emissions. Finally, Section 2.6 contains an assessment of scenario planning as a modeling methodology.

2.1 Quantifying Carbon Emissions

CO_2e emissions associated with freighting goods can be quantified using various methodologies. The most accurate methodology for estimation of CO_2e is to calculate the fuel usage associated with the conveyance of goods. Although this is the most accurate method, fuel consumption data is not available for this analysis. Due to the use of third-party logistics providers in the transportation network, our modeling utilizes activity-based carbon accounting methodologies. Activity-based modeling has three primary inputs to CO_2e calculation: Weight, distance, and the mode-specific emissions factor (Bouchery et al., 2018).

At Roche, carbon accounting was suggested to be completed using the activity-based approach outlined by the United Kingdom's Department for Environment, Food and Rural Affairs (UK DEFRA). Specifically, the DEFRA 2021 UK Government Conversion Factors for greenhouse gas (GHG) reporting are used in our CO_2e calculations. This activity-based emissions model allows for the calculation of CO_2e based on the specific mode of transport used in Brazil. DEFRA also specifies that the scope of emissions should be identified based on the GHG Protocol Corporate Accounting and Reporting Standard. (Department for Environment Food & Rural Affairs, 2022). The GHG Protocol Corporate Standard document outlines that our transportation model would fall under the scope of three emissions. Scope three GHG emissions are classified by the (World Resources Institute, 2015, p. 25) as:

> "An optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company but occur from sources not owned or controlled by the company."

Since our modeling is accounting for the use of third-party logistics providers, calculations are based on version two of the scope three freighting goods 2021 conversion factors (Department for Environment Food & Rural Affairs, 2022). All calculations follow the general activity-based formulation of weight, distance, and the mode-specific emissions factor. The emissions factors selected were the average-laden figures, meaning that we are assuming that the delivery vehicles have a set capacity utilization half the available volume of the vehicle. For more information on the understanding of vehicle capacity utilization, Section 2.1.1 covers vehicle utilization in depth.

Within the DEFRA 2021 conversion factors used, some important assumptions are stated. Particularly, in aviation CO_2e emissions calculations, direct emissions such as CO_2, CH_4 and

N_2O are modeled in addition to indirect non-CO_2 emissions such as water vapor, contrails, and NO_x. It is noted that there is significant scientific uncertainty around the indirect effect of non-CO_2 aviation emissions so this number should be revisited in coming years to ensure accuracy. Currently, including indirect non-CO_2 aviation emissions raises the emissions factor by 90% over just using direct emissions (Department for Environment Food & Rural Affairs, 2022).

The final aviation specific adjustment to consider is an uplift factor. When utilizing the great-circle distance in aerial distance calculations, the Intergovernmental Panel on Climate Change (IPCC) suggests implementing an uplift factor adjustment of 9-10% to account for indirect flight paths, delays/congestion/circling of aircraft. Instead of using 9-10%, DEFRA recommends utilizing an uplift factor of 8% on top of the great-circle distance. (Department for Environment Food & Rural Affairs, 2022).

2.1.1 Vehicle Utilization: Network for Transport Measures Carbon Accounting

CO_2e calculations being based on aggregate activity-based measures serve to help identify hot spots of emissions within the transportation network. In activity-based calculations such as DEFRA, the number of trips made by vehicles does not impact the resulting carbon emissions of the transportation route. This is due to not considering the variation of load factors between freight shipments. In this context, a load factor is the percentage utilization of a vehicle based on the carrying capacity of the vehicle and the weight of the freight. Specifically, DEFRA emissions factors are not dynamic, meaning total CO_2e calculations are completed by selecting an average load factor of vehicles with no adjustments for the size of individual shipments from the distribution center to nodes of demand.

Another methodology that can be used to account for the load factor of vehicles is the Network

of Transport Measures methodology (NTM). NTM is a more detailed activity-based carbon

accounting approach that leverages fuel consumption, distance travelled and weight per

shipment. The fuel consumption variable considers vehicle type, load factor, and road type

associated with freight transportation. Within the methodology, NTM discusses how "The

weight-based load factor has a significant impact on both fuel consumption and pollutant

emissions. This is of particular importance to consider for heavy duty vehicles…" (Network for

Transport Measures, 2015). Although the NTM methodology has more detail than the DEFRA

methodology, using NTM for carbon accounting requires additional data inputs of road type and

the specific vehicles used in each shipment.

Vehicle type modeling in NTM is used to identify a vehicle specific emissions factor like the

DEFRA methodology, however, NTM methodology has the added value of splitting the

emissions calculation into a fixed and variable component. This allows for modeling of

emissions in a way that accounts for a difference between sending ten pallets on ten trucks versus

ten pallets on one truck. This is explored in detail in a paper by Velazquez-Martinez et al., 2013.

A simplified version of the NTM equation is provided for clarity, expressed in Equation 1 as:

$$TE = TE_{fixed} + EF_{var} * w \qquad (1)$$

Where TE is total emissions, and the TE_{fixed} accounts for the number of shipments, modeling

emissions of an empty vehicle. The EF_{var} accounts for the variable shipment emissions

associated with transporting cargo weight expressed by *w* (Velazquez-Martinez et al., 2013).

2.2 Calculation of Center-of-Gravity Analysis (CoG) and Visualization of Location Data

Center-of-Gravity (CoG) analysis is a methodology that can be used to calculate the center of a series of latitude-longitude pairs. The software selected for this calculation is the *Mean Center Spatial Statistics package* from ArcGIS Pro 3.1. ArcGIS was selected primarily for ease of the visualization of data, and it also allows for the creation of weighted latitude-longitude pairs. Figure 1 displays a visualization of a weighted versus unweighted mean center, and Figure 2 provides the calculations associated with CoG analysis in the ArcGIS *Mean Center Spatial Statistics package* (ArcGIS, 2023).

Figure 1

Unweighted and Weighted Center-of-Gravity Visualization (ArcGIS, 2023).
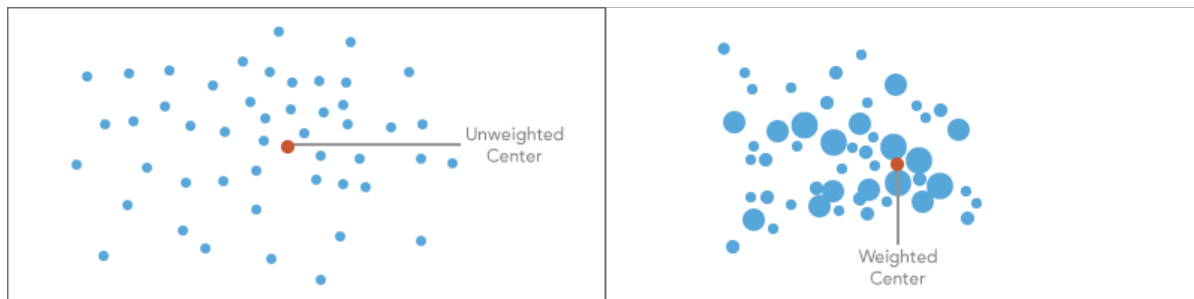
Figure 2

Calculation of Weighted Mean Center (ArcGIS, 2023).

The Mean Center is given as:

$$\bar{X} = \frac{\sum\limits_{i=1}^{n} x_i}{n} \quad , \quad \bar{Y} = \frac{\sum\limits_{i=1}^{n} y_i}{n} \tag{1}$$

where x_i and y_i are the coordinates for feature i, and n is equal to the total number of features.

The Weighted Mean Center extends to the following:

$$\bar{X}_w = \frac{\sum\limits_{i=1}^{n} w_i x_i}{\sum\limits_{i=1}^{n} w_i} \quad , \quad \bar{Y}_w = \frac{\sum\limits_{i=1}^{n} w_i y_i}{\sum\limits_{i=1}^{n} w_i} \tag{2}$$

where w_i is the weight at feature i.

2.3 Quantifying Patient-Centricity

Patient-centricity was selected as a metric due to its critical importance to Roche. In a 2015 study by Deloitte, a broad shift to increasing patient-driven health care was identified in the United States, Canada, the UK, and Brazil. This increasing patient-driven health care is intended to satisfy the needs of patients who value transparency and convenient care (Morris et al., 2015).

Provided the trend for patient-centric health care, we conducted analysis of the implications of patient-centricity on supply chain operations. According to a 2021 Accenture report, "Patient-centric supply chains focus on delivering the right therapy to the right patient at the right time to the right place and at the right price." (Srivastava et al., 2021). From the perspective of a pharmaceutical supply chain, it is clear patient-centric transportation of products must reach patients geographical needs while maintaining short lead times associated with transit. Ensuring short lead times and high geographical availability of products would imply the assessment of

inventory levels and service level as potential ways to assess patient-centricity. Inventory and service level optimization are widely researched and reviewed as methods to improve the availability of pharmaceuticals to patients in need.

For example, a model created in 2017 by Nematollahi et al. communicates that the high service level associated with a socially responsible pharmaceutical supply chain has dramatic impact on the costs associated with inventory both for retailers and distributors. The multi-objective model has a "Social objective" to maximize service level, and the "economic objective" to maximize the profit of the pharmaceutical supply chain (Nematollahi et al., 2017). More detailed methods such as the work by (Campelo et al., 2018) focus on the last mile routing of pharmaceutical delivery vehicles and the tradeoff of distance traveled and route duration of vehicles while ensuring service level agreements are still maintained.

It is clear through research on other inventory/service level optimization techniques that this is a possible way to assess the patient-centricity performance of a supply chain. Despite this, the scope of our research is not to identify optimal inventory levels and provide high service levels by optimizing routing, but rather to quantify the taxation and CO_2e emissions associated with transportation within Brazil. Therefore, service levels, stocking lead times and inventory optimization are not considered in our modeling. Patient-centricity is assumed as an input based on the timeliness of delivery comparison between air and road shipments, and location of delivery based on modeling introduction of new cities that have not been distributed to before. For more details on assumptions of the patient-centric model see Section 3.6.4.

2.4 Modeling Taxation Within Brazil

As discussed in Section 1.1.2, taxation has a major impact on the way supply chains are designed in Brazil. A 2020 study from Furlanetto et al. of the impact of taxation in Brazil considers the facility allocation question as the primary input to a quantitative model. This model is based on a multicommodity, multilink network of distribution for an animal feed company, and three scenarios were compared to identify an optimal location of distribution based on the minimization of taxation within the network. Findings of the modeling suggest that there is a clear need to make decisions regarding distribution within Brazil based on the existing tax structure, due to results showing substantial losses to companies when optimization is conducted without including tax considerations (Furlanetto et al., 2020). In lieu of conducting optimization, scenarios from our modeling provide taxation differential analysis between selected distribution center locations.

2.5 Tradeoff between Transportation Cost and Carbon Emissions

Supply chain research on the relationship between cost and carbon is robust, as transportation emissions and the cost associated with freight transport are often variables targeted in optimization techniques. Prior to addressing optimization, Section 2.5.1 addresses the general correlation between cost and carbon in a transportation network. Section 2.5.2 analyzes the relevance of carbon emissions in transportation mode selection criteria. Finally, Section 2.5.3 addresses optimization techniques for transportation cost and carbon emissions.

2.5.1 Correlation between Cost and Carbon

Intuitively, there is a distinct correlation between cost and carbon within transportation networks. This correlation is present due to fuel being a 24% contributor to cost for trucking providers, and

fuel usage being the primary metric used to calculate carbon emissions. (Williams & Murray, 2020) A study by (Wygonik & Goodchild, 2011) investigates this relationship between cost, carbon emissions and service quality in an urban pickup and delivery transportation network. Findings of this research include the visualization shown in Figure 3, and a direct relationship between one kilogram of carbon emissions and three dollars and fifty cents of transportation cost. According to (Wygonik & Goodchild, 2011), "The results demonstrate there is not a trade-off between CO_2 emissions and cost, but that these two metrics trend together."

Figure 3

Relationship between Dollars and Kilograms of CO_2 (Wygonik & Goodchild, 2011).
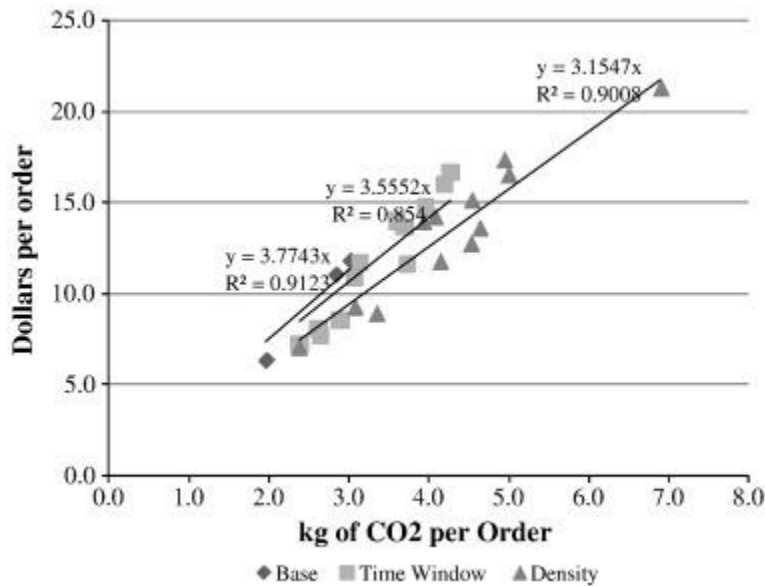
2.5.2 Relevance of Carbon Emissions in Transportation Mode Selection

Section 2.5.1 outlines research on how carbon and cost are correlated in transportation networks, leading to the question of the relevance of carbon emissions in transportation mode selection. Research conducted in 2012 considers how emissions regulations such as a carbon tax may

impact mode selection within supply chains. Findings of this research suggest that although carbon regulation may incentivize switching to different modes, the decision is often informed by non-monetary considerations such as lead time. The quantification of this research suggests that one or more of the base parameters such as weight, distance travelled, or unit transportation cost needs to be extremely high to incentivize selecting a different transportation mode. (Hoen et al., 2012) In summary, the research suggests that the addition of carbon regulations is likely not significant enough to encourage shippers to change their selected transportation mode.

2.5.3 Optimization Techniques for Cost and Carbon

Current best practices on calculating the tradeoff between cost and carbon in supply chains are often based around mixed integer linear programming (MILP) optimization techniques. When using MILP models, scenarios may be adjusted using multi-objective approaches. Multi-objective approaches allow for optimizing values of carbon footprint and the cost of distribution when given a set number of distribution centers and customers. An example of this type of modeling is seen in a MILP model Ramudhin et al. produced in 2009. By implementing a goal programming solution to the model, the multi-objective approach was able to achieve a tradeoff between cost and carbon footprint while maintaining control over operational costs in the model (Ramudhin et al., 2009).

A similar but more sophisticated multi-objective optimization model was created by Rahimi et al. in 2017. This more detailed model uses multi-objective optimization of service level, GHG emissions, and profit associated with the distribution of perishable products. An important finding of this research is that results of multi-objective MILP models can be interpreted in different ways depending on the judgmental weight that a model user assigns to each objective

present in the model (Rahimi et al., 2017). This is critical in understanding how the MILP optimization works. Although MILP can provide optimized results, the optimization is dependent on the weights associated with the input variables.

2.6 Scenario Planning

When comparing MILP optimization to scenario planning, the MILP modeling is theoretically proven and auditable as a method to optimize decisions based on current-state inputs. Scenario planning still relies on the allocation of weights to selected input variables; however, it offers more flexibility in changing multiple variables to assess future scenario states.

Scenario planning is utilized in our modeling due to our desire to capture broad trends and large shifts in the way product may be distributed in Brazil. An article by Schoemaker in *MIT Sloan Management Review* discusses the way scenario planning may be used to adjust multiple variables at one time, capturing new states that may be present after large shocks or deviations from the status quo. Therefore, scenario planning allows for subjective interpretation of potential futures that management may want to strategically prepare for (Schoemaker, 1995). Modeling of shifts to patient-centricity, new product introductions, and assessing the taxation impacts on the distribution network are all future states that lend themselves well to scenario planning. Despite these future states being ideal for scenario planning, it is important to note that scenario planning has some limitations that are listed in literature. Notably, scenario planning does not have an explicit theoretical foundation, and it is difficult to replicate and judge outcome decisions that arise from modeling (Chermack et al., 2001). To counter the challenge of replication, our methodology for all calculations has been outlined in Chapter 3. We intend to ensure that the judgment of results may be replicated by Roche.

CHAPTER 3: METHODOLOGY

The methodology for developing the CO_2e emissions and taxation model starts with data initialization, with Section 3.1 describing the required data inputs to the model. Next, Section 3.2 contains information on how data is visualized and the identification of a location for a consolidated distribution center. After all the data is prepared for inclusion in the model, various scenarios dictate what modeling takes place. All scenarios calculate CO_2e, distance, and taxation as outlined in Sections 3.3, 3.4, and 3.5, respectively. Finally, the detailed methodology behind each scenario is described in Section 3.6.

3.1 Initialization of the Model

The modeling of the supply chain in Brazil is dependent on the inclusion of many data fields from the pharmaceutical and diabetes divisions. Data instrumental to the operation of the model include the following fields: shipments and associated destination cities, weight and temperature control requirements of the shipments, and invoice value. Data must be cleaned so that daily deliveries are aggregated by analyzing all deliveries to one destination city per day of the year.

3.1.1 Summary of Variables

Following are the variables used for modeling CO_2 emissions for all the scenarios:

CO_2e (road): CO_2 equivalent for road transportation

CO_2e (inflight): CO_2 equivalent for flight transportation

CO_2e (air): Total CO_2 equivalent for air transportation

a: Air delivery

r: Road delivery

i: Origin node coordinates

j: Destination node coordinates

I: Invoice value

I_{ij}: Total invoice value for goods delivered from origin node i to destination node j

I_r, I_{nr}: Invoice value for refrigerated and non-temperature-controlled deliveries respectively

W_r, W_{nr}: Weight for refrigerated and non-temperature-controlled deliveries respectively

i_a, i_r: Maximum shipment value in air and road shipment

o: Outbound days

d_r: Refrigerated deliveries

d_n: Non-temperature controlled deliveries

D: Distance

W: Weight

$W_{o,j}$: Total weight shipped to the destination city j on outbound day o

k: Circuity factor for adjusting road distance

u: Uplift factor for adjusting air distance

h_{ij}: Haversine distance from origin node to destination node

d_{ij}: Road distance from origin node to destination node considering the circuity factor, k

f_{ij}: Flight distance from origin airport to destination airport considering the uplift factor, u

r_e: Road emissions factor

a_e: Air emissions factor

r_n: Road emissions factor, non-temperature-controlled

r_t: Road emission factor, temperature-controlled

a_n: Air emissions factor non-temperature-controlled

a_t: Air emissions factor temperature-controlled

n_air: Number of deliveries for air shipment

n_road: Number of deliveries for road shipments

k_1, k_2, k_3: Distance covered in km for first, second and third leg of air deliveries

t_k: Total kilometers

t_{ij}: Tax% for goods delivered from origin state i to destination state j

V: Tax amount

p: Product family

n_p: No of deliveries for new product family

c_p: Convenio tax percentage for a product family p

t_e: Effective tax amount

$I_{f,j}$: Invoice distribution factor for destination city j

$I_{p,j}$: Invoice value for a product family p for last year for destination city j

$E_{n,j}$: Estimated Invoice value for new product for a city j

$P_{v,n}$: Projected Invoice value for new product n

$W_{e,j}$: Estimated weight of new product introductions delivered to any city j

W_v: Approximate weight(kg) per \$R value for new product introductions

O_v: Expected average order value per delivery

p_j: Population of a city j

$p_{f,j}$: Population distribution factor for a city j

3.1.2 Data Collection on Brazilian Cities and Airports

For understanding the demographics of the Brazilian population served by the supply chain network, data from Kaggle Brazilian cities was utilized (Parada, 2022). This data allows us to filter cities by many demographic features. The next dataset leveraged is the Brazilian airport dataset that is compiled from the Civil Aviation agency. Utilizing the dataset involves a Rstudio package called flightsbr (Pereira, 2022). Out of the 503 airports present in the airport dataset, 42 were identified as being utilized in pharmaceutical distribution, and these are the only ones included in the modeling. If required, additional airports can be loaded into the dataset to update the operational network.

3.1.3 Latitude-Longitude Mapping

For the latitude-longitude mapping of demand nodes within Roche's operational network, data was collected manually from the following data sources:

- https://simplemaps.com/data/world-cities (Pareto Software, LLC, 2023).
- Brazil city and airport datasets mentioned in Section 3.1.2
- Google Maps (Google Maps, 2023).

3.2 Data Visualization

Data is plotted using ArcGIS software to visually represent the locations of airports, distribution centers, and customer demand nodes. Conceptualization and presentation of data to Roche were performed with ArcGIS Story Maps. ArcGIS was also used to identify the weighted center-of-gravity (CoG) for the location of a proposed new warehouse location. This proposed location is strategically situated at the weighted center of the invoice value from the diabetes and pharmaceutical divisions. Each city of customer node demand is therefore weighted based on the

total invoice value of combined division demand that is shipped to each city. Figure 4 below

contains a visualization of the two current distribution center locations used in the base case

scenarios as well as the suggested new CoG.

Figure 4

Visualization of Selected Airports and Distribution Centers

3.3 CO₂e Emissions Calculations

Emissions calculations are based on emission factors that are specific to the mode of transportation. The emissions factors are further segmented into categories based on the temperature requirements of the shipment. Emissions calculations for both categories are done separately and then added together to present the final emissions estimate. Table 1 lists the emissions factor for each delivery mode as well as the temperature condition requirements.

Table 1

CO₂e Emission Factors (DEFRA 2021)

CO2e Emission Factors	kg CO₂e
Air Short Haul	2.55439
HGV (>7.5 - 17 tonnes), Diesel Average laden	0.42240
HGV Refrigerated (>7.5 - 17 tonnes), Diesel Average laden	0.50306
Average Vans (up to 3.5 tonnes), Diesel	0.74994

Calculations for the CO_2e emission present in the network follow the formula: weight multiplied by distance and a mode-specific emissions factor. Equations 2 and 4 explain CO_2e calculation followed in the model for air and road mode of delivery. Important to note that this does not account for the fixed emissions component of vehicle emissions, which can be done following NTM methodology explained in section 2.1.1 if vehicle details are known. For all equations of CO_2e and distance, variable i differs based on the scenario being analyzed. For example, Equation 2 calculations have variable i represent the origin node of the distribution center. This is either the pharmaceutical base case location in Goias, the diabetes base case location in Santa Catarina, or the CoG location based in Minas Gerais.

$$CO_{2e} \ (road) = \sum_o \sum_j W_{o,j} * d_{ij} * r_n \ + \ \sum_o \sum_j W_{o,j} * d_{ij} * r_t \quad \forall \ \{o,j\} \qquad (2)$$

The road delivery emission calculation considers all the deliveries being sent from a selected

distribution center directly to the destination cities. For air deliveries, emissions calculations are

in three parts: the first leg of transportation is road delivery from distribution center to nearest

airport, the second leg is in-flight air transportation from origin airport to destination airport

(Equation 3) and the third leg is road delivery from destination airport to destination city. Hence,

the total CO_2e for air is the summation for all the three parts (Equation 4). For more details on

the distance calculations used in the three legs of air transportation refer to Section 3.4.2. For

Equation 4, $CO2e(road)3rdLeg$ is based on an origin of the destination airport, a factor later

explained by Equation 11 in Section 3.4.2.

$$CO_{2e} \ (inflight) = \sum_o \sum_j W_{o,j} * f_{ij} * a_n \ + \ \sum_o \sum_j W_{o,j} * f_{ij} * a_t \quad \forall \ \{o,j\} \qquad (3)$$

$$CO_{2e} \ (air) \ = \ CO2e(road)1stLeg \ + \ CO2e(inflight)2ndLeg \ + \ CO2e(road)3rdLeg \ (4)$$

3.4 Distance and Delivery Calculations

As outlined in Figure 5, distance calculations follow the logic of one central distribution center.

However, the distribution center location, departure airports, destination cities, and product

categories all vary between scenarios. The calculation for the number of deliveries varies by

mode, temperature requirement, and the mode-specific maximum shipment value policies

applied on the invoice value of the shipment. The following h_{ij} formula (Equation 5) is using the

Haversine formula in Excel to find the great-circle distance (in kms) on the sphere of the earth

between two latitude-longitude pairs *i,* representing the origin node and *j,* representing the

destination node. The Haversine formula is generally used to estimate the great-circle distance

between two latitude-longitude pairs. The great-circle distance considers the spherical shape of the Earth, allowing for the estimation of surface distance (Yap, 2003). The great-circle distance between points is used as a proxy of distance traveled for plane travel between airports. Section 3.4.1 discusses road distance calculations, and Section 3.4.2 addresses the distance calculations for aerial shipments.

$$h_{ij} = ACOS\left(COS\left(RADIANS(90 - lat(i))\right) * COS\left(RADIANS(90 - lat(j))\right) +\right.$$

$$SIN\left(RADIANS(90 - lat(i))\right) * SIN\left(RADIANS(90 - lat(j))\right) *$$

$$\left. COS\left(RADIANS(long(i) - long(j))\right)\right) * 6371 \quad\quad (5)$$

Figure 5

Distance Calculations Model
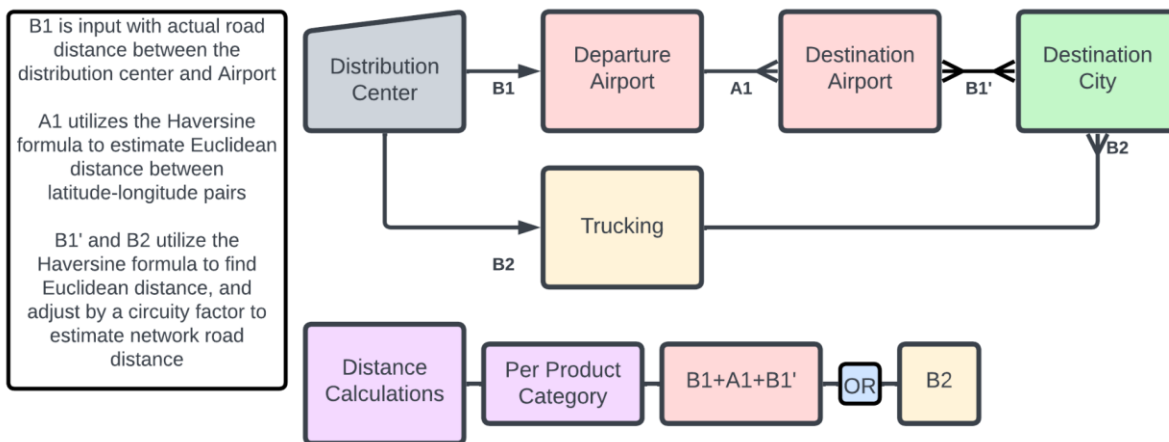
3.4.1 Road Distances and Deliveries

Road travel cannot use the great-circle distance between points since trucks do not travel following linear paths. To adjust for road travel, the "networked distance" is calculated by

adjusting great-circle distance by a circuity factor (k). Circuity factors vary by geography, and for the Brazilian road network a k of 1.23 is applied to adjust great-circle distance to an estimation of networked road distance. (Ballou, 2002). Great-circle calculation is completed using Equation 5. Road distance is then estimated by using a circuity factor adjustment to the calculated great-circle distance (Equation 6).

$$d_{ij} = k \cdot h_{ij} \tag{6}$$

All deliveries being sent on one day to one city are modeled to be consolidated into one delivery vehicle, with the caveat that there can be no sharing between temperature requirements. Road deliveries are therefore divided into two primary categories: non-controlled shipments at 15-25°C and controlled shipments at 2-8°C, depending on the temperature requirements of the product being shipped. Road consolidation also considers a maximum shipment value (i_r) of maximum Brazilian Reals (R\$) in invoice value that can be loaded on one truck. This i_r assumption was created with input from the Roche team, not due to physical constraints of the vehicles. Considering this, the number of deliveries for road shipment is calculated as per Equation 7.

$$n\_road = \left\lceil \frac{I_{r,r}}{i_r} \right\rceil + \left\lceil \frac{I_{n,r}}{i_r} \right\rceil \tag{7}$$

Finally, total kilometers covered by road deliveries is calculated by taking the number of deliveries and multiplying them by the road distance of the specific route.

$$t_k = n\_road \cdot d_{ij} \tag{8}$$

3.4.2 Air Distance and Deliveries

Air shipments are broken into three delivery legs, considering the different modes of transportation and vehicles required to transport products from the distribution center to final customers. For the first delivery leg, shipments are transported by trucks via road from the distribution center to the nearest departure airport. Deliveries on a given day are combined and sent together, with a constraint for temperature-controlled and non-temperature-controlled products being transported on separate trucks. The distance from the distribution center to the departure airport is calculated using the real road network length as obtained from Google Maps.

For the second leg, we calculate the great-circle distance from the departure airport to the closest destination airport to the destination city. The closest destination airport is determined using Equation 11. This great-circle distance is then multiplied with an uplift factor (u) in (Equation 9). The uplift factor represents an adjustment margin to account for real world flight conditions, adding a fixed percentage to the great-circle distance. In the context of flight distance estimation, applying an uplift factor to the great-circle distance can account for factors such as wind, air traffic control restrictions, deviations from the planned route, and other factors that may cause the actual distance traveled by the flight to be longer than the straight-line distance between the two points.

Finally, the third leg of delivery, i.e., destination airport to the destination city, is mapped using the road methodology expressed in Section 3.4.1. Maximum shipment values for consolidation are the same as road for the first leg and the last leg of shipment, however, for second leg, a new maximum shipment value (i_r) R$ worth of invoice value is specified for air freight. Equation 10 represents the calculation for number of air deliveries, n_{air} considering these factors.

$$f_{ij} = u \cdot h_{ij} \tag{9}$$

$$n\_air = \left\lceil \frac{I_{r,a}}{i_a} \right\rceil + \left\lceil \frac{I_{n,a}}{i_a} \right\rceil \tag{10}$$

An important component required for calculating the air emissions is identifying the destination airport, as all the underlying distance calculations are done considering the location of destination airport. Modeling the destination airport for each city is completed by calculating the distance of each destination city j from each airport i and identifying the airport which has the minimum distance to the destination city (Equation 11). This airport is then referenced as the destination airport for all deliveries to city j.

$$Airport\ i\ corresponding\ to\ \arg\min(h_{ij}) \ \forall \ \{j : destination\ city\} \tag{11}$$

Total distance (in kms) covered by air deliveries is the sum of distances covered in each leg of delivery for the selected nine-month time period. Equation 17 represents the total distance covered to deliver the products to customers by air mode.

First leg delivery distance:

$$k_1 = n\_road * d_{ij} \tag{12}$$

Second leg:

$$k_2 = n\_air \cdot f_{ij} \tag{13}$$

$$f_{ij} \quad \forall \quad \begin{cases} i = origin\ airport, \\ j = nearest\ destination\ airport\ as\ selected\ by\ formula\ 11 \end{cases} \tag{14}$$

Third leg:

$$k_3 = n\_road \cdot d_{ij} \tag{15}$$

$$r_{ij} \quad \in \quad \left\{ \begin{array}{c} i = nearest\ destination\ airport\ as\ selected\ by\ formula\ 11, \\ j = destination\ city, \end{array} \right\} \tag{16}$$

$$t_k = k_1 + k_2 + k_3 \tag{17}$$

3.5 Taxation Calculations

No taxes in Brazil are modeled other than the ICMS rates, for further understanding of this modeling constraint Section 1.1.2 discusses taxation in detail. Section 2.4 contains the understanding of prior research modeling supply chain taxation in Brazil. Taxation in the modeled network is calculated by using an ICMS table shown by Table 2 below. This table references the taxation associated with shipping products from the origin state to the destination state, and the three rows highlighted in green are the three selected DC locations, GO standing for the Goias DC used for the pharmaceutical division, SC standing for Santa Catarina DC used for diabetes distribution, and MG standing for Minas Gerais for the new DC based on the CoG location. Hence, to calculate total tax amount, invoice value of all the products delivered from the state where the distribution center (DC) is located to the final customer state is multiplied with the corresponding state tax percentage for the origin destination state pair (Equation 18).

$$t_a = \sum_i \sum_j I_{ij} * t_{ij} \quad \forall \quad i, j : \{states\ in\ brazil\} \tag{18}$$

Modeling must also consider taxation convenios. The tax exemption for specific product families under convenios are modeled to implement adjustments to the ICMS tax rate. The tax amount

calculated in Equation 18 is multiplied with the convenio tax percentage for that product family. The convenio percentage associated with any product family is a variable that can be adjusted. Considering the convenios on top of tax amount, the effective tax amount, t_e is defined in Equation 19.

$$t_e = \sum_i \sum_j I_{ij} * t_{ij} * c_p \;\; \forall \;\; \begin{Bmatrix} i.j : states\ in\ Brazil \\ p : products \end{Bmatrix} \tag{19}$$

Table 2

ICMS Tax Table: Expressed in Percentage ICMS, Row Origin State, Column Destination State.

State Abbr.	AC	AL	AM	AP	BA	CE	DF	ES	GO	MA	MG	MS	MT	PA	PB	PE	PI	PR	RJ	RN	RO	RR	RS	SC	SE	SP	TO	Average
AC	19	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.26
AL	12	19	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.26
AM	12	12	20	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.30
AP	12	12	12	18	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.22
BA	12	12	12	12	19	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.26
CE	12	12	12	12	12	18	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.22
DF	12	12	12	12	12	12	18	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.22
ES	12	12	12	12	12	12	12	17	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.19
GO	12	12	12	12	12	12	12	12	17	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.19
MA	12	12	12	12	12	12	12	12	12	20	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.30
MG	7	7	7	7	7	7	7	7	7	7	18	7	7	7	7	7	7	12	12	7	7	7	12	12	7	12	7	8.33
MS	12	12	12	12	12	12	12	12	12	12	12	17	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.19
MT	12	12	12	12	12	12	12	12	12	12	12	12	17	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.19
PA	12	12	12	12	12	12	12	12	12	12	12	12	12	19	12	12	12	12	12	12	12	12	12	12	12	12	12	12.26
PB	12	12	12	12	12	12	12	12	12	12	12	12	12	12	18	12	12	12	12	12	12	12	12	12	12	12	12	12.22
PE	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	18	12	12	12	12	12	12	12	12	12	12	12	12.22
PI	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	21	12	12	12	12	12	12	12	12	12	12	12.33
PR	7	7	7	7	7	7	7	7	7	7	12	7	7	7	7	7	7	19	12	7	7	7	12	12	7	12	7	8.37
RJ	7	7	7	7	7	7	7	7	7	7	12	7	7	7	7	7	7	12	20	7	7	7	12	12	7	12	7	8.41
RN	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	20	12	12	12	12	12	12	12	12.30
RO	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	18	12	12	12	12	12	12	12.20
RR	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	20	12	12	12	12	12	12.30
RS	7	7	7	7	7	7	7	7	7	7	12	7	7	7	7	7	7	12	12	7	7	7	18	12	7	12	7	8.33
SC	7	7	7	7	7	7	7	7	7	7	12	7	7	7	7	7	7	12	12	7	7	7	12	17	7	12	7	8.30
SE	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	22	12	12	12.37
SP	7	7	7	7	7	7	7	7	7	7	12	7	7	7	7	7	7	12	12	7	7	7	12	12	7	18	7	8.33
TO	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	20	12.30

3.6 Scenario Overview

The scenarios differ in the quantity and type of data being leveraged. Scenarios were selected based on addressing the posed research questions while maintaining a useful model output for the supply chain department at Roche.

3.6.1 Base Case Scenario: Pharmaceutical Division Control Group

The pharmaceutical base case scenario follows the methodology outlined in Sections 3.1-3.5. Origin i for this scenario is the distribution center located in GO.

3.6.2 Base Case Scenario: Diabetes Division Control Group

The diabetes base case scenario follows the methodology outlined in Sections 3.1-3.4.1. Diabetes scenario modeling does not include any air mode deliveries. The ICMS calculation table from Section 3.5 still applies, however, since currently, taxation convenios are only applicable to the pharmaceutical division, no convenios are applied to the diabetes scenario. Origin i for this scenario is the distribution center located in SC.

3.6.3 Consolidation Scenario

The consolidation scenario combines the diabetes and pharmaceutical divisions historical volume and utilizes a hypothetical DC located at the weighted CoG of the combined business divisions' invoice value distribution. Details on the calculation of the CoG are in Section 2.2. A new origin airport was selected based on its closest proximity to the selected CoG. Origin i for this scenario is the distribution center located in MG following Section 3.2 weighted CoG calculations.

3.6.4 Patient-Centricity Scenario with New Product Introductions

Within our modeling process, the initial patient-centricity scenario exclusively used a product specific approach to adjust the demand of existing diabetes division products. This modeling extrapolated a new decentralized product distribution scenario based on the distribution of diabetes division demand across Brazil. The assumption behind this modeling was rooted on the high prevalence of one in ten adults in Brazil living with diabetes. (International Diabetes

Federation, 2021). The high prevalence of the disease and the widespread distribution of Roche's diabetes division sales lead us to assume modeling following this distribution would imply patient-centric distribution.

Despite the high prevalence of diabetes, 32% of people living with diabetes in Brazil are undiagnosed (International Diabetes Federation, 2021). Paired with feedback from Roche and this large underrepresentation of true diabetes diagnoses, we decided to move away from modeling diabetes division demand as a proxy for patient-centricity. Our finalized patient-centric scenario modeling introduces new variables that aren't exclusively based on using a product specific approach to modeling patient-centricity.

This patient-centricity scenario considers the forecasted growth of new product pipelines at Roche. Our research uses two approaches: the first one is to model based on the existing demand distribution from a current similar product, and the second one is to model distribution to new demand nodes that have not been served before. Distribution for new demand nodes is modelled based on a demographic filter. The demographic filter used in the scenario is a population filter, with any city over 50,000 people being modeled into the scenario. The model also includes an air delivery adjustment factor defining the maximum distance limit for road deliveries. Any shipments for distances above this limit of 500 KM are delivered by air, any below by road. The tool segregates cities based on distance from the distribution center using the unadjusted great-circle distance. The final new input is a weight-to-invoice value ratio. The assumption for the scenario is an average weight-to-invoice ratio as established by historical averages.

All new inputs for the patient-centricity scenario are summarized in Table 3. Specifically, these inputs are classified into three parts, new product introduction, new city distribution, and finally, air delivery adjustment. The new product introduction has inputs that integrate distribution

demand modeled after an existing product in the Roche pipeline, for this scenario an existing

product category was selected. The projected invoice value is the hypothetical forecasted value

of total sales associated with the new product introduction being modeled.

Table 3

Input Variables for Modeling Patient-Centric Scenario.

Input Category	Input Parameter	Input value	Units
New Product Introduction	Most similar product family	Historical	Categorical
	Projected Invoice value	50,000,000	R$
	Weight-to-Invoice Ratio	Historical Avg.	kg/R$
	Average Order size	300,000	R$
New City Distribution	Projected Invoice value	50,000,000	R$
	Weight-to-Invoice Ratio	Historical Avg.	kg/R$
	Demographic Filter	50,000	People
	Maximum shipment value	Historical Avg.	R$
Air Delivery Adjustment	Adjustment for NPI	No	Yes/No
	Adjustment for New City	Yes	Yes/No
	Road vs. Air Boundary	500	km

Modelling new product distribution requires a weight-to-invoice ratio as well as an average order

size per delivery assumptions. The average order size serves the same function as i_r, i_a

(maximum shipment value) in the prior scenarios to identify total number of deliveries, n_p.

(Equation 20).

$$n_p = \sum_j \frac{E_{n,j}}{O_v} \tag{20}$$

New product introduction requires using data from a similar product family category. This input

must be tied to Roche's historical product mix and sales for that similar product family category.

Sales from a similar product family from the previous year are used to calculate an invoice

distribution factor for a city (Equation 21). This factor is then multiplied with total projected

invoice value of NPI to get an estimated invoice value for new product in a city (Equation 22).

$$I_{f,j} = \frac{I_{p,j}}{\Sigma_j I_{p,j}} \quad \forall\, j \tag{21}$$

$$E_{n,j} = P_{v,n} * I_{f,j} \tag{22}$$

The estimated invoice value for the city (calculated in equation 22) and the NPI weight-to-

invoice ratio is used to calculate the estimated weight of NPI (w_e) delivered to any city (Equation

23).

$$W_{e,j} = E_{n,j} * W_v \tag{23}$$

CO_2e calculations follow a similar methodology as Section 3.3. However, in the case of NPI, the

deliveries are not summed up on a daily level. The calculations are based on multiplying the total

weight delivered to a city over a given period with the distance from origin to the destination and

the emission factor as per the delivery and temperature shipment requirement of the product

(Equation 24 and 25).

$$CO2e\,(road) = \Sigma_j\,W_j * d_{ij} * r_e \quad \forall\,\{j\} \tag{24}$$

$$CO2e\,(inflight) = \Sigma_j\,W_j * f_{ij} * a_t \quad \forall\,\{j\} \tag{25}$$

Modeling the introduction of new cities into the distribution network is completed with the

addition of a demographic filter from the Kaggle Brazilian cities dataset. New cities are then

geocoded into the model by utilizing the filter. For this scenario, the demographic filter is set to

population size, so the introduction of new cities is based on the population of the city. The

population of these cities is then used to calculate the population distribution factor, which

represents the percentage of population of a given city with respect to all other cities above the

demographic filter (Equation 26). Specific city-based invoice values are calculated for new cities

as per Equation 27 considering the population distribution factor and the projected invoice value

of the NPI.

This scenario also includes a delivery adjustment factor to define the air and road deliveries

based on a boundary radius from the origin distribution center. For example, setting a boundary

for road versus air deliveries of 500km would imply all cities less than 500km away from the

distribution center would utilize road, and all cities greater than 500km away would utilize air

mode of delivery.

$$p_{f,j} = \frac{p_j}{\Sigma_j p_j} \quad \forall j \tag{26}$$

$$E_{n,j} = P_{v,n} * p_{f,j} \tag{27}$$

CHAPTER 4: RESULTS

Prior to discussing results, the assumptions made for our various scenarios are listed in Section 4.1. After these assumptions are clarified, Section 4.2 contains the scenario analysis results, and finally, Section 4.3 conveys potential limitations to the methodology.

4.1 Assumptions

The most general assumptions are regarding the geography served by modeling. Specifically, all scenario planning is conducted for Brazil operations of Roche, considering only transportation from the distribution center(s) to the customer. This excludes the importation of products, and all transportation of manufactured products from the manufacturer to the distribution center. Demand nodes are mapped from actual customer demand across Brazil; however, actual addresses are not used, and demand nodes are aggregated by the city the customer is located in. This assumption implies last mile distance for deliveries is not considered in the model.

As shown in Figure 5, aerial shipments are modeled using only one airport that is close to the distribution center. All road shipments are modeled using the road distance between the distribution center and the destination city. Although the number of deliveries is being modeled to each city, altering deliveries does not impact the consolidation assumption of the vehicles used. Therefore, the number of deliveries does not impact vehicle space utilization. The assumptions made regarding consolidation are outlined in Equations 6 and 9. It is important to note that actual vehicle consolidation and space utilization is an unverifiable assumption without data input from regional third-party logistics providers, which is why it is not included in modeling.

Following the discussion of potential emissions methodologies from Section 2.1 DEFRA methodology, the vehicle emissions factors used remain constant between all scenarios, and an average laden assumption is used regarding load factor of the vehicles. Emissions factors for aerial shipments use exclusively cargo freight numbers, although actual distribution relies on including freight on passenger flights (Roche, 2022). Taxation assumptions are following ICMS VAT rates discussed in Section 2.4; that is, convenios are only applied on pharmaceutical division product categories in all scenarios. Taxation assumptions are based on product category-wide convenios agreements. Therefore, convenios based on a subset of a product family cannot be modeled in any scenario. We are only able to assess taxation on a product category basis.

4.2 Scenario Analyses

Appendix A contains results from all scenarios in a consolidated table format, as segregated by the three main scenario categories. All invoice value and tax figures in this section are expressed in millions of Brazilian Reals (R$). Scenarios provide estimates based on the research assumptions and the methodology above, and do not represent actual values associated with operations.

4.2.1 Base Case Scenario Analysis

The results of the base case scenarios display a clear difference in mode selection between diabetes and pharmaceutical divisions. Table 4 displays how in the diabetes division, no shipments are routed by air. Despite this, the diabetes division has high CO2e emissions from road transportation. This is due to the total weight being transported, which is approximately six times higher than that of the pharmaceutical division for road deliveries. The taxation variance

44

between divisions is large, due to the differential in total invoice value distributed by each division.

Table 4

Calculated Base Case Scenario Output for Pharmaceutical and Diabetes Divisions.

Scenario with DC Location	Mode of transport	Metric Tons of CO_2e	Invoice Value	Unadjusted Tax	Convenio Adjusted Tax	Weight (Kilograms)	Total Kilometers	Number of Deliveries
Pharmaceutical Division (GO)	Air	605	1,100	132	81	193,949	2,737,306	3,736
	Road	65	1,982	239	151	154,603	1,380,144	1,330
	Total	669	3,081	371	232	348,552	4,117,450	5,066
Diabetes Division (SC)	Road	503	352	37	-	937,818	7,227,396	4,784
	Total	503	352	37	-	937,818	7,227,396	4,784
Combined Total (GO+SC)	Air	605	1,100	132	81	193,949	2,737,306	3,736
	Road	568	2,334	276	151	1,092,421	8,607,540	6,114
	Total	1,173	3,434	408	232	1,286,370	11,344,846	9,850

4.2.2 Consolidation Scenario

Modeling a single warehouse and consolidating the current pharmaceutical and diabetes distribution to the existing pharmaceutical distribution center (DC) results in an estimated 2.9% reduction in CO_2e emissions and a 3.9% increase in taxation when compared to the combined base case scenario from Table 4. The consolidation in the existing pharmaceutical DC also results in the reduction of the total number of deliveries by 3.4% due to synergizing transportation between the divisions. The increase associated with taxation is caused by the lower ICMS rates of distribution from the current diabetes distribution center (SC) when compared to the current pharmaceutical DC (GO) (8.29% and 12.19% respectively).

Using the consolidation scenario, a comparison between the existing distribution center and the new CoG distribution center can be made. As seen in Table 5, moving from the existing DC location to the new location conveys a 23.4% reduction in CO_2e emissions and a 10.1% decrease in unadjusted tax. This improvement in CO_2e is primarily driven by a reduction of kilometers traveled, with a total difference of 13.5%. The taxation varies due to a switch from the existing DC located in Goais where pharmaceuticals currently are distributed from to the hypothetical DC in Minas Gerais as decided by the CoG analysis. Section 5.3 explores the impacts of consolidation of the business divisions.

Table 5:

Calculated Output for Consolidation of Distribution Centers.

Scenario with DC Location	Mode of transport	Metric Tons of CO_2e	Invoice Value	Unadjusted Tax	Convenio Adjusted Tax	Weight (Kilograms)	Total Kilometers	Number of Deliveries
Existing Distribution Center (GO)	Air	604	1,100	132	81	193,949	1,382,427	3,736
	Road	535	2,334	293	204	1,092,421	7,722,907	5,776
	Total	1,139	3,433	424	286	1,286,370	9,105,333	9,512
New Distribution Center (MG)	Air	457	1,100	119	73	193,949	1,136,011	3,736
	Road	417	2,334	266	184	1,092,421	6,742,401	5,776
	Total	873	3,433	385	257	1,286,370	7,878,412	9,512

4.2.3 Patient-Centricity Scenario with New Product Introductions

The patient-centricity scenario with new product introductions has an additional set of assumptions as well as new input variables for the scenario. New inputs and associated assumptions are described in Section 3.6.4 and presented in Table 3.

Modeling patient-centricity explores new product introductions and distribution to new cities.

Following the results displayed in Table 6, the model estimates twenty-four metric tons of CO_2e

for the demand being modeled on an existing product family demand, and a fifty-six metric ton

CO_2e impact of modeling shipments to new cities. With all else being equal, adding new cities

accounts for 69.1% of the emissions of the patient-centric scenario due to the more distributed

demand. Although not pictured in the table, the NPI component of the model assumes delivery to

87 unique cities, and the new city component assumes delivery to 666 unique cities.

Table 6:

Calculated Output for Patient-Centric Scenario.

Scenario with DC Location	Mode of transport	Metric Tons of CO_2e	Invoice Value	Unadjusted Tax	Convenio Adjusted Tax	Weight (Kilograms)	Total Kilometers	Number of Deliveries
New Product Introductions	Air	20	19	2	-	7,081	85,141	107
	Road	4	31	4	-	11,653	94,984	114
	Total	24	50	6	-	18,735	180,125	221
New City Distribution	Air	56	47	6	-	17,489	159,006	676
	Road	0.1	3	0	-	1,246	10,993	39
	Total	56	50	6	-	18,735	169,999	715
Combined Total	Air	77	66	8	-	24,570	244,147	783
	Road	4	34	4	-	12,899	105,977	153
	Total	81	100	12	-	37,469	350,124	936

4.3 Limitations

Some limitations of our modeling process are outlined in this Section, and potential areas for

improvement based on limitations are discussed further in Section 6.2. Our first limitation is that

modeling does not consider inventory. Therefore, stockouts and service level cannot be modeled,

and these are two aspects identified that can impact patient-centric distribution. Modeling does

have the capability to calculate the number of consolidated deliveries, however, vehicle types for

utilization assumptions were not available in the data. If exact vehicle types for each delivery were available for all shipments, actual CO_2e emissions could be identified on a granular level based on fuel usage. Due to this limitation, this modeling of CO_2e is primarily useful in identifying hot spots of scope three emissions within Brazil and not for exact calculations.

Originally modeling was conducted to account for the utilization of two airports. Inclusion of this routing for multiple departure airports was dropped from modeling. Similarly, the modeling of a local and destination hub for road shipments would allow for more accurate routing of vehicles. While possible to include hubs and multiple locations for airports and road hubs, this level of detail would result in a more specific MILP model that could optimize for one variable holding other variables constant. Due to our utilization of scenario planning, we avoided adding extra hub locations for clarity and transparency in extrapolation of future scenarios. This avoidance limits the accuracy associated with the model calculations. Additionally, modeling of patient-centricity does not consider costs of operating distribution centers. With the assumption of one airport and one distribution center, scenarios can only adjust speed of order fulfillment by adjusting the amount of air shipments. Another possible solution not considered in modeling is the inclusion of regional distribution centers that are geographically situated to allow for rapid order fulfillment using trucking.

The primary theme of the research is the cost and carbon implications of a patient-centric supply chain. Despite this, freight cost was not a variable that could be modeled with accuracy in our scenario planning due to the uncertain impacts of third-party logistics pricing. Section 2.5.1 provides insight into assigning a fixed monetary cost per kilogram of CO_2e with the assumption that there is a linear relationship, but no such assumption was included to estimate the cost of

transportation for Roche. For decision-making on the optimal patient-centric supply chain, this is a large limitation to the model utility.

In the consolidation scenario, the center-of-gravity location is a latitude-longitude coordinate that is not located in a developed logistics area. The airport selection for this scenario is based on the closest airport. When looking at the physical location of the suggested distribution center and the associated airport, it likely would not be a suitable location for a pharmaceutical distribution center. Therefore, the model may require finetuning of the suggested distribution center locations for optimal assessment of the consolidation scenario. The final listed aerial limitation is that Roche currently leverages passenger flights to carry goods, however, utilization of passenger flight cargo is one that is not is included in the modeling.

CHAPTER 5: DISCUSSION

The Discussion chapter starts with Section 5.1, exploring the patient-centric scenario. Section 5.2 finalizes the discussion regarding vehicle utilization within the network. Section 5.3 examines consolidation of the pharmaceutical and diabetes business divisions, and the impact of that consolidation on taxation and CO_2e emissions.

5.1 Patient-Centricity

Patient-centricity is dependent on location and timing, with higher patient-centricity served by delivery close to the patient that demands a specific product. Many customers of Roche's pharmaceuticals division are in areas with high population density, and customers are often hospitals and medical distributors. The patient-centricity scenario allows for detailed demand modeling of more personalized healthcare solutions by modeling cities that fulfill certain demographic requirements. The demographic filter we chose was population, but future iterations of the model can leverage other data points such as GDP per capita, number of post offices, etc.

Results of modeling show a clear association between increased patient-centricity and increased carbon emissions in the transportation network. This led us to consider potential ways to hedge against the increased emissions. A 2017 article by Plessis et al. discusses how end to end visibility is critical in a patient-centric supply chain:

> "Essentially, capturing information about the patient journey and gaining an understanding of patient needs will help to develop a true patient-led strategy within the industry and design solutions that treat the patient and not just the disease." (Plessis et al., 2017, p. 464).

One potential way to capture end to end visibility could be integrating reverse logistics into the model. When modeling emissions and taxation in the network, reverse logistics can be considered due to savings in CO_2e associated with being able to reuse temperature sensitive packaging and some medical components. Reverse logistics can be seen as a touch point that can help capture information about the patient's journey. The product is closest to the patient right after the packaging is stripped away, so through understanding the reverse logistics of material we have insight into the behavior of the patient. This has increasing relevance when we look toward increasing personalized healthcare deliveries, and we hypothesize that this integration of reverse logistics may additionally help mitigate the CO_2e impact of distribution by allowing for reuse of materials.

In addition to the reverse logistics considerations, modeling patient-centricity conveys a need for a flexible and responsive supply chain. Leveraging aerial shipments for faster deliveries at the scale required for a full transition to patient-centricity would imply an increase in Roche's reliance on third-party logistics partners, and less reliance on an internally managed fleet of road vehicles.

5.2 Vehicle Utilization Impact on CO_2e

We suggest detailed vehicle utilization modeling should not be included in CO_2e calculations unless vehicle type and capacity are known. If vehicle type and capacity are known, utilization should be modeled with a carbon emissions framework that considers the difference between driving an empty and a full truck, such as the NTM methodology discussed in Section 2.1.1. The best possible way to capture the complexity of vehicle utilization would be to measure the fuel usage associated with a delivery, however, due to reliance on third-party logistics providers this is not a feasible quantification technique. In the absence of data related to vehicle type and

capacity, we suggest using the emission factors associated with average load and a general vehicle type used for a shipment mode.

5.3 Consolidation of Business Divisions

Consolidation of pharmaceutical and diabetes division into one existing central distribution center showed minor improvements in CO_2e emissions (2.9%) and an increase in taxation (3.9%) in comparison to the base case. CO_2e consolidation is influenced by road deliveries being consolidated into less overall shipments, additionally, consolidation reduces the overall distance that is being traveled over the road.

Moving the consolidated distribution center to Minas Gerais, based on the weighted center-of-gravity, produced a 10.1% improvement in unadjusted taxation, due to the lower ICMS tax rates in that state. Minas Gerais has an average ICMS rate of 8.33% across distribution to all states, compared to a 12.19% rate when distributing from Goais, as seen in Table 2. This differential suggests that consolidation of pharmaceutical and diabetes divisions within Minas Gerais is beneficial for minimizing environmental impact while maximizing profit. Critical to this scenario and as expressed in Section 4.3, the limitation of this result is that the CoG located in Minas Gerais is not located in a developed logistical region, and the closest airport may not have the scale or routing sufficient for Roche's air freight demand.

CHAPTER 6: CONCLUSION

In this chapter, we present some managerial recommendations in Section 6.1, followed in Section 6.2 by a discussion of our model's limitations and suggestions for future research that could expand on our research.

6.1 Managerial Implications

Scenario planning for increasing patient-centric demand has illuminated a correlation between patient-centricity and CO_2e emissions. Analysis suggests that taxation is not impacted directly by patient-centricity, however, within Brazil, taxation has a significant impact on the decision of where to locate a distribution center. Specifically, consolidating all distribution to a center-of-gravity location in the state of Minas Gerais is associated with a 10.1% decrease in unadjusted taxation, and 23.4% decrease in CO_2e emissions. Following the assumption of correlated cost and CO_2e emissions addressed in Section 2.5.1, the Minas Gerais scenario provides an opportunity for cost, taxation and CO_2e savings in a pharmaceutical supply chain.

In addition to providing insight into the distribution center location decision, modeling using scenario planning provides the flexibility to adjust parameters in preparation for an uncertain future. Assuming a future that prioritizes patient-centricity, our research emphasizes the importance of tracking vehicle utilization in the supply chain. Patient-centricity is associated with more distributed demand and shorter lead times, potentially incentivizing integration of corporate strategies such as reverse logistics. Decentralized demand and a reliance on air transportation encourages management of a supply chain that is reliant on third-party logistics providers instead of company owned fleets, since low vehicle utilization of fleet resources would be associated with high freight cost and CO_2e emissions.

6.2 Future Research

This section will delve into some potential improvements that can be made generally to the model and methodology, then, three additional scenarios are suggested for future analysis.

The main area for improvement in modeling technique is the accuracy of the estimated CO_2e emissions and taxation. Section 2.1.1 discusses the benefits of utilizing the NTM protocol, which would allow for consideration of load factor of freight transport, and therefore, more accurate carbon accounting. Section 2.4 explores how modeling taxation in Brazil should not be limited to State ICMS taxes. Therefore, a comprehensive model of taxation would significantly improve the utility of modeling transportation costs.

Utilizing multi-objective MILP modeling and adjusting one variable in each iteration as discussed in Section 2.5.3 would allow for more accurate modeling of the base case and consolidation scenarios. This MILP technique would allow for inclusion of multiple departure airports and regionalization of hubs for road transit, which can add value when looking at base case analysis. MILP was not utilized due to our research requiring multiple variables being adjusted at once to portray certain scenarios, leading to us deciding to utilize the scenario planning discussed in Section 2.6. Finally, forecasting scenarios over multiple years and applying simulation or system dynamics modeling techniques would allow for robust planning to pair with sales forecasts and new product introductions. Simulation and system dynamics can be used as tools to help assess the implications of future carbon tax regulations and forecast for broad industry trends that may be relevant to Roche's operations in Brazil. Although not directly researched in Chapter 2, the implementation of simulation or systems dynamics could be a viable way to help assess the most accurate inputs to the patient-centricity scenario.

Independently or in conjunction with the potential model improvement techniques, three additional scenarios are suggested for future research. The first proposed scenario is adding model functionality to route localized demand to regional hubs, particularly for dense regions such as greater Sao Paulo. Creation of one regional hub in Sao Paulo may have large CO_2e and cost reductions due to high concentration of demand and population density in the region.

The second scenario is the addition of the diagnostics business division to the consolidation scenario. Compiling all divisions operations and modeling the diagnostics division base case scenario finalizes the model for the entirety of Brazil. As mentioned in Section 1.2, this scenario will involve some additional data cleaning to ensure accurate modeling of equipment sales, service agreements and repairs associated with the division sales.

The third and final proposed scenario is life-cycle analysis of products and associated temperature sensitive packaging within the supply chain. The CO_2e emissions associated with expanded polystyrene (EPS) packaging and potential for reuse require estimation of CO_2e and cost savings from avoided re-manufacturing. Modeling CO_2e of EPS would also require analysis of the cost and emissions associated with transporting packaging materials using reverse logistics to regional reprocessing centers. Until a reverse logistics and product life-cycle scenario is completed it is not clear if integration of reverse logistics may reduce the CO_2e or cost within the transportation network.

The aim of our project's research was to estimate the impact on CO_2e in various scenarios considered by Roche. Our contribution highlights the value of scenario planning for sustainable supply chain design. Modeling the supply chain using scenario planning is modular, allowing Roche to include distribution scenarios from across Brazil, providing estimates of CO_2e while still accounting for taxation policy in scenario planning exercises. Additionally, this project

focuses on patient-centricity and the resulting impact on the environment and Roche's

transportation costs. The results from our analysis can benefit the company in prioritizing

transportation decisions in a more sustainable way, allowing for a comprehensive understanding

of scope three emissions and operations within Brazil.

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Appendix

Appendix A: Model Output

Table 7

Consolidated Output for all the Modelling Scenarios

Scenario Category	Scenario with DC Location	Mode of transport	Metric Tons of CO_2e	Invoice Value	Unadjusted Tax	Convenio Adjusted Tax	Weight (Kilograms)	Total Kilometers	Number of Deliveries
Base Case Control Groups	Pharmaceutical Division (GO)	Air	605	1,100	132	81	193,949	2,737,306	3,736
		Road	65	1,982	239	151	154,603	1,380,144	1,330
		Total	669	3,081	371	232	348,552	4,117,450	5,066
	Diabetes Division (SC)	Road	503	352	37	-	937,818	7,227,396	4,784
		Total	503	352	37	-	937,818	7,227,396	4,784
	Combined Total (GO+SC)	Air	605	1,100	132	81	193,949	2,737,306	3,736
		Road	568	2,334	276	151	1,092,421	8,607,540	6,114
		Total	1,173	3,434	408	232	1,286,370	11,344,846	9,850
Consolidation of Diabetes and Pharmaceuticals	Existing Distribution Center (GO)	Air	604	1,100	132	81	193,949	1,382,427	3,736
		Road	535	2,334	293	204	1,092,421	7,722,907	5,776
		Total	1,139	3,433	424	286	1,286,370	9,105,333	9,512
	New Distribution Center (MG)	Air	457	1,100	119	73	193,949	1,136,011	3,736
		Road	417	2,334	266	184	1,092,421	6,742,401	5,776
		Total	873	3,433	385	257	1,286,370	7,878,412	9,512
Patient-Centricity	New Product Introductions (GO)	Air	20	19	2	-	7,081	85,141	107
		Road	4	31	4	-	11,653	94,984	114
		Total	24	50	6	-	18,735	180,125	221
	New City Distribution (GO)	Air	56	47	6	-	17,489	159,006	676
		Road	0.1	3	0	-	1,246	10,993	39
		Total	56	50	6	-	18,735	169,999	715
	Combined Total (GO)	Air	77	66	8	-	24,570	244,147	783
		Road	4	34	4	-	12,899	105,977	153
		Total	81	100	12	-	37,469	350,124	936