# PROJECT/PRESCRIPTIVE DECISION ANALYTICS

OPTIMUM ALLOCATION OF MANUFACTURING PLANT LOCATIONS AND DISTRIBUTION

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# EXECUTIVE SUMMARY

This project describes a model that employs linear programming to resolve a network problem, determining the optimum allocation of manufacturing plant production numbers and the optimum distribution of units to meet demand for automotive manufacturers. It analyses a hypothetical scenario closely based on the situation of supply chain and logistics of a German automaker. The model aims to reduce both financial cost and $CO_2$ emissions. The model is able to produce considerable reductions to financial cost and particularly substantial reductions to $CO_2$ emissions relative to schemes that do not use linear programming. It could be improved by using more detailed data to cover a greater scope, and it could potentially be adapted to make further improvements to supply chain and distribution networks by focusing on different network elements to further improve the efficiency.

# PROJECT

## Introduction

In this project, prescriptive analytics will be used to solve a problem related to factory assignment and service network design for a globally operating automotive manufacturer. In this scenario, München Motoren (MM) is an automotive manufacturer based in Germany and a competitor of BMW. In the past, it manufactured all its cars within Germany but now owns a set of manufacturing plants around the world. For one of its most popular models, the Class 3 compact car, it generally manufactured all cars in the respective regions in which they were to be sold and shipped them to regional hubs which would then deliver the cars within the region.

For the next generation of the Class 3, MM have identified some potential points for improvement. Firstly, while the regions generally make sense, there are some points which may be causing unnecessary costs in shipping, and new plants have been built that could potentially be utilised.

Secondly, industries are increasingly being required to reduce greenhouse gas emissions in order to combat climate change. This naturally places pressure on the automotive industry and while the main focus is on developing zero-emission vehicles (Vidovic, 2021), the logistical supply chain is also being placed under the spotlight (Dunn, 2022). Freight transportation is a significant contributor to carbon dioxide emissions and companies could reduce emissions and cost by looking at alternative shipping arrangements (Demir, et al., 2016, p. 790). MM would like to work out the most optimal locations to produce cars and subsequently the most optimal distribution network in terms of both cost and $CO_2$ emissions, looking at both rail and marine shipping modes.

This report will present a linear optimisation model that incorporates elements of assignment problems (Newton, 2021) and service network design problems (Farvolden & Powell, 1994, p. 256). It will take in focus on the costs—both financial and environmental—of transport to work out the optimal allocation of vehicle production to global manufacturing plants and subsequently the optimal distribution to regional demand hubs. The model is used to produce optimal solutions in terms of financial cost, $CO_2$ emissions, and a balance of the two. The model uses average cost and emissions data per tonne-kilometre and applies it to the length (in kilometres) of the land and sea shipping routes between nodes. It also calculates general labour costs of production at the facilities confirmed.

The model in this report serves to provide a good general model or where to build the cars and how to deliver them on a global level, however it should be noted that it does not cover the entire supply chain, and it could benefit from more comprehensive, first-hand information from automotive makers and logistics companies. Nonetheless, it will give a good guide on how to use linear programming to increase the financial and environmental efficiency of building and delivering cars when they are manufactured and delivered worldwide.

## Problem Definition and Model

Globalisation has had a significant impact on the automotive industry. These days, automobile manufacturers have expanded production from their home countries to make cars in several countries to save on labour costs and meet demand in emerging markets (Socco, 2017). The German car industry is certainly no exception. BMW operates 31 manufacturing plants worldwide (BMW Group, 2021, p. 36). Mercedes-Benz has a production network extending to four continents (Mercedes-Benz Group AG, 2015). The Volkswagen Group, itself incorporating a range of global brands these days, runs 120 production plants worldwide (Volkswagen Group Rus, 2023). This has turned the supply chains of automakers into complex networks that may require complex methods to use efficiently.

Traditionally, financial cost has been the primary concern for manufacturers when optimising supply chains, but recently environmental sustainability has also become a major issue (Umpfenbach, et al., 2018, p. 272). Many automotive manufacturers, including BMW (BMW Group, 2021, p. 39), are aware of this and are actively making efforts to make their businesses more sustainable. Automakers have been pursuing methods to make their supply chains “greener” not only for their own interests, but also for their customers (Simpson, et al., 2007, p. 29).

The shipping industry is similarly concerned, with freight transportation being a large source of greenhouse gases (Greene, 2023). The industry is looking into multimodal transportation as a way to be more environmentally friendly (Demir, et al., 2016, pp. 789-790), with the low emissions of rail transportation in particular focus (ESCAP, 2021, p. 14). When focusing on lowering emissions in the distribution of freight, rail transportation should also be considered for the solution.

Linear programming models are a popular method for solving the network problems that pervade supply chain management and logistics (Cardoso Pires & Morosini Frazzon, 2016, p. 198). Such methods have been used to model green intermodal service network design problems for freight transport (Demir, et al., 2016), as well as to model an entire supply chain in the building of cars (Masoud, 2014). Therefore, to solve this problem that relates to automotive supply chain logistics, it would be advantageous to adapt a transportation problem with elements of assignment (Newton, 2021) and network design problems. The nature of this problem is suitable for using data to analyse ideal scenarios, making it a good fit for resolution by prescriptive analytics (Segal, 2022).

## Solution Approach

This problem is fundamentally a network problem. It can be expressed with nodes as both supply and demand notes, and the costs involved in transporting units between the nodes to meet demand can be expressed as constraints of a network problem. This makes a network problem-based approach the most suitable solution (Newton, 2021, p. 1). The solution will be determined using the simplex method through the Excel Solver add-in.

In this scenario, the automaker MM has 18 demand nodes spread across four regions. Cars are transported to these demand nodes then to be distributed locally.

| No. | Code | City | Country | Region | Demand areas served | Demand (thousands of cars annually) |
|---|---|---|---|---|---|---|
| 1 | MUN | Munich | Germany | Europe | Germany, eastern and northern Europe | 82 |
| 2 | CHE | Chennai | India | Asia | India, Indian subcontinent | 9 |
| 3 | BKK | Bangkok | Thailand | Asia | South-east Asia | 9 |
| 4 | DAL | Dalian | China | Asia | Northern China | 86 |
| 5 | TAM | Tampico | Mexico | Americas | Central America | 5 |
| 6 | SAV | Savannah | United States | Americas | South-eastern United States | 20 |
| 7 | ARA | Araquari | Brazil | Americas | South America | 4 |
| 8 | DUR | Durban | South Africa | Other | Southern Africa | 1 |
| 9 | GOA | Genoa | Italy | Europe | Southern Europe, France | 48 |
| 10 | LON | London | United Kingdom | Europe | UK, Ireland, Iceland | 51 |
| 11 | MOS | Moscow | Russia | Europe | Russia, Belarus | 9 |
| 12 | HKG | Hong Kong | China | Asia | Southern China including Hong Kong/Macau, Taiwan | 85 |
| 13 | BUS | Busan | South Korea | Asia | South Korea, Japan | 26 |
| 14 | LAX | Los Angeles | United States | Americas | South-western United States | 21 |
| 15 | SEA | Seattle | United States | Americas | North-western United States, western Canada | 20 |
| 16 | MON | Montreal | Canada | Americas | North-eastern United States, eastern Canada | 21 |
| 17 | SYD | Sydney | Australia | Other | Australia and New Zealand | 4 |
| 18 | DBI | Dubai | United Arab Emirates | Other | Middle East and northern Africa | 5 |

*Figure 1: Demand nodes*

Of these, 6 nodes are also supply nodes—they have manufacturing sites which are capable of building the “Class 3” model cars. Munich has a larger production capacity as it is home to many plants. Whereas the factory in Dalian, China has been expanded to meet production capacity in China.

| No . | Code | City | Country | Region | Demand (x1000 units) | Materials ($/unit) | Labour ($/unit) | Emissions (kg-$CO_2$) | Production (x1000 units) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Min. | Max |
| 1 | MUN | Munich | Germany | Europe | 82 | 25000 | 2554.2 | 330 | 1 | 210 |
| 2 | CHE | Chennai | India | Asia | 9 | 25000 | 48.6 | 330 | 5 | 10 |
| 3 | BKK | Bangkok | Thailand | Asia | 9 | 25000 | 232.2 | 330 | 5 | 10 |
| 4 | DAL | Dalian | China | Asia | 86 | 25000 | 228.6 | 330 | 5 | 230 |
| 5 | TAM | Tampico | Mexico | Americas | 5 | 25000 | 223.2 | 330 | 5 | 70 |
| 6 | SAV | Savannah | United States | Americas | 20 | 25000 | 1305 | 330 | 5 | 145 |
| 7 | ARA | Araquari | Brazil | Americas | 4 | 25000 | 230.4 | 330 | 5 | 10 |
| 8 | DUR | Durban | South Africa | Other | 1 | 25000 | 282.6 | 330 | 5 | 20 |

*Figure 2: Supply nodes*

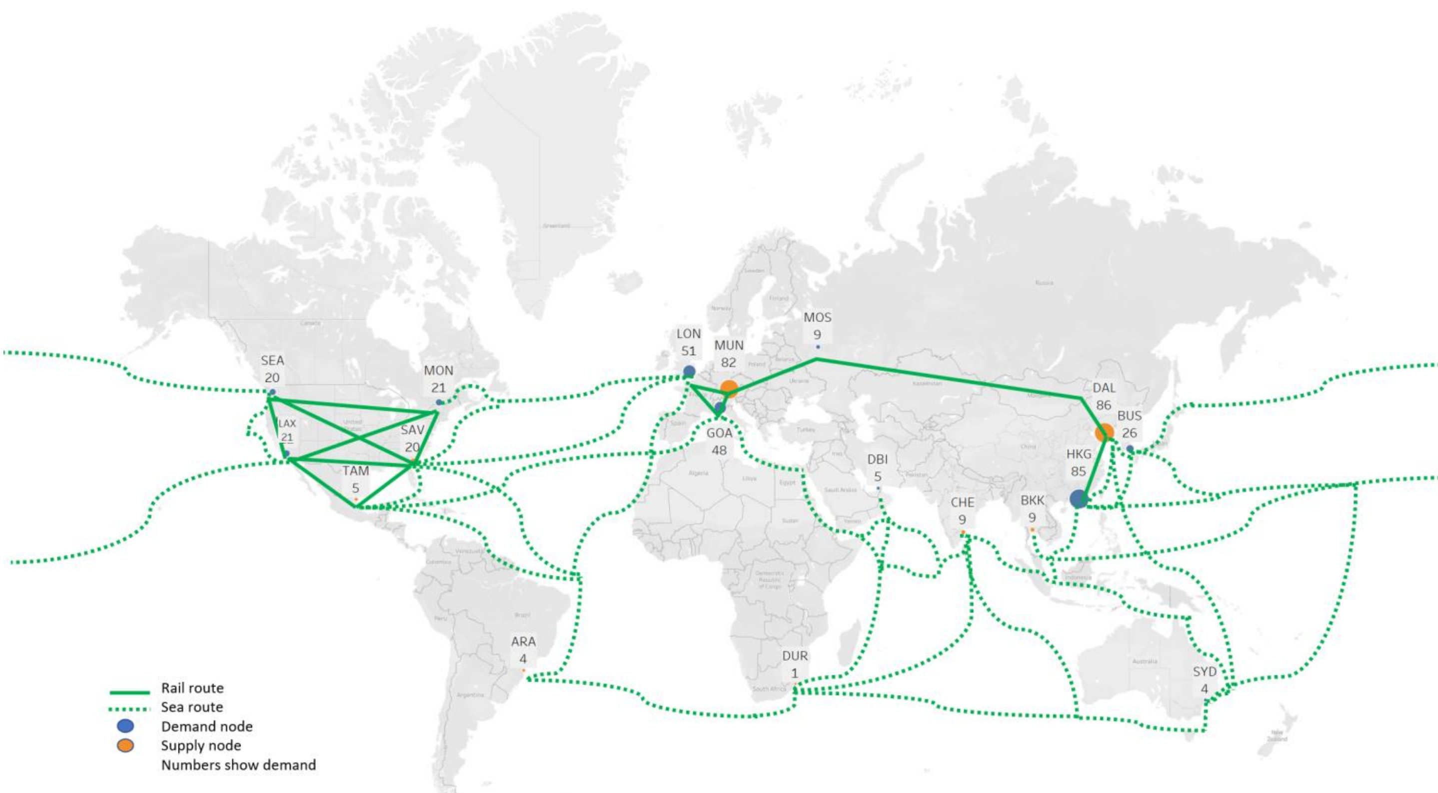


*Figure 3: Map of shipping routes (Map: © Mapbox and Openstreetmap)*

See Appendix 0 and Appendix 3 for the bases of figures estimated.

Nodes are given the following notation. Uppercase characters denote the set, whereas lowercase characters denote one node.

- $X/x$ supply nodes
- $Y/y$ demand nodes
- $I/i$ origin node
- $J/j$ destination node

All nodes aforementioned are demand nodes, and can be origin and/or destination nodes. Only the nodes with manufacturing plants in Figure 1 are supply nodes.

Other parameters are given the following notation.

- $d$ demand (thousands of units of cars)
- $s$ supply (thousands of units of cars)
- $c$ cost (USD/$ for manufacturing and labour per 1,000 units)
- $e$ emissions (kg-$CO_2$e [kilograms of carbon dioxide-equivalent] per 1,000 units)
- $g$ total cost
- $h$ total emissions
- $w$ weighting assigned to emissions
- $t$ total weighted cost
- $m$ large number coefficient (here, 999)
- $p$ minimum required supply
- $q$ maximum required supply

The primary decision variables are the manufacturing plants and the distribution routes.

- *F* manufacturing plant output (thousands of units)
- *R* shipping route load (thousands of units)

There are auxiliary decision variables used to control the constraint where production must be either 0 or above the minimum production value. See the Production limits constraint below.

- *A* binary variable for production limit constraint

The objective function is to minimise the total weighted cost of production and distribution of the vehicles, which is the weighted sum of cost and emissions of each manufacturing plant and each route.

$Minimise\ t = (1-w)g + wh$, or:

$$Minimise\ t = (1-w)\left(\sum_{x\in X} c_x F_x + \sum_{i\in I, j\in J} c_{i,j} R_{i,j}\right) + \mathrm{w}\left(\sum_{x\in X} e_x F_x + \sum_{i\in I, j\in J} e_{i,j} R_{i,j}\right)$$

The model is subject to the following constraints.

$Subject\ to$:

a. (Balance) $s_X = d_Y = 506$
b. (Supply) $F_X = s_X;\quad F_X = 506$
c. (Demand) $y \in Y: s_y = F_y + \sum_{i\in I} R_{(i,y)} - \sum_{j\in J} R_{(y,j)} = d_y$
d. (Production limits) $x \in X:\ F_x = 0 \vee p_x \leq F_x \leq q_x$
    i. (Acceptable if 0) $x \in X: F_x \leq mA_x;\ \ F_x \leq 999A$
    ii. (Above min. if not 0) $x \in X:\ F_x \geq A_x p_x$
    iii. (Below max.) $x \in X:\ F_x \leq q_x$
    iv. (Binary) $x \in X: A_x = \{0,1\}$
e. (Integer)
    i. $x \in X: F_x = 1 \dots n$
    ii. $i \in I, j \in J: R_{i,j} = 1 \dots n$
f. (Non-negativity)
    i. $x \in X: F_x \geq 0$
    ii. $i \in I, j \in J: R_{i,j} \geq 0$

The details of these constraints are explained as follows.

a. Balance: This is a balanced network problem, so the total supply must equal total demand, which is 506,000 units.
b. Supply: The total of the manufacturing plant output decision variables must equal the total supply, which is again 506,000 units.
c. Demand: For each demand node, the supply must equal demand. This is the manufacturing output if the node is also a supply node, plus the total supply of any routes for which the node is a destination (i.e., incoming supply), less the total supply of any routes for which the node is an origin (i.e., outgoing supply).
d. Production limits: For each supply node, there is a minimum output required (5,000 for all except Munich, which is 1,000) for the plant to be employed for production of the car model. There is also a maximum capacity set at about 1/3 of the total production capacity of the plant(s) in that city. Munich's minimum is lower as it is the site where the cars are designed. However, the base constraint (output must be 0 or between the minimum and maximum) is non-linear when expressed in this way. Therefore, this model will use a zero-one algorithm to allow for the two alternative decisions. We will place binary decision variables, $A$, for each supply node, that Solver can modify to satisfy the conditions (josliber, 2014).
    i. With this equation, a value of 0 for the supply node output would satisfy the equation whether $A$ is 0 or 1. For any value above 0, $A$ must be 1. (The large number *m* is set at 999, above the maximum supply of any supply node.)
    ii. With this equation, a value below the minimum limit $p_x$ must have $A$ set to 0 to satisfy the equation, but this would not be possible given i. above.
    iii. As in a normal equation, the value must not exceed the maximum limit $q_x$.
    iv. The variable $A$ must be binary.
e. Integer: Primary decision variables must be integers. While the nature of this problem would allow for the variables to be divisible by 1,000, economies of scale would suggest that the cars should be produced and shipped in batches.
f. Non-negativity: Primary decision variables must be non-negative.

The following assumptions were made for this model.

a. Aside from labour, the manufacturing of the cars is the same amount in any region. That is, the parts procurement section of the supply chain is assumed to be the same. With the correct data, the number could be entered into the model as is.
b. The "last mile" from the regional hub to the final destination (e.g., a dealer) is not incorporated into this model.
c. Shipping costs and emissions are based on averages per tonne-kilometre and do not take into account pricing for certain routes.
d. After-service costs which account for differences in manufacturing is not included in the scope of this model.

## Interpretation of the Results

Before the linear programming analysis, a baseline, or "business-as-usual (BAU)" scenario was created.

| Units | Origin | Destination | Mode | Cost | Emissions |
|---|---|---|---|---|---|
| **224** | **Pro** | **MUN** | **Pro** | **$ 27,554,200.00** | **330,000.0** |
| **171** | **Pro** | **DAL** | **Pro** | **$ 25,228,600.00** | **330,000.0** |
| **70** | **Pro** | **TAM** | **Pro** | **$ 25,223,200.00** | **330,000.0** |
| **21** | **Pro** | **SAV** | **Pro** | **$ 26,305,000.00** | **330,000.0** |
| **20** | **Pro** | **DUR** | **Pro** | **$ 25,282,600.00** | **330,000.0** |
| 26 | BKK | HKG | Sea | $ 70,579.39 | 595,696.0 |
| 35 | CHE | BKK | Sea | $ 133,176.43 | 1,124,020.4 |
| 85 | DAL | HKG | Sea | $ 80,518.70 | 679,584.7 |
| 15 | DUR | CHE | Sea | $ 222,243.97 | 1,875,758.0 |
| 4 | DUR | SYD | Sea | $ 359,334.33 | 3,032,812.2 |
| 29 | GOA | CHE | Sea | $ 271,013.53 | 2,287,377.2 |
| 5 | GOA | DBI | Sea | $ 211,892.67 | 1,788,392.1 |
| 26 | HKG | BUS | Sea | $ 57,138.15 | 482,250.8 |
| 82 | MUN | GOA | Rail | $ 47,482.09 | 11,506.6 |
| 51 | MUN | LON | Rail | $ 94,037.19 | 22,788.5 |
| 9 | MUN | MOS | Rail | $ 243,178.32 | 58,930.6 |
| 21 | SAV | LAX | Rail | $ 401,074.27 | 97,194.2 |
| 21 | SAV | MON | Sea | $ 105,238.22 | 888,219.5 |
| 20 | SAV | SEA | Rail | $ 482,545.70 | 116,937.6 |
| 4 | TAM | ARA | Sea | $ 334,022.57 | 2,819,178.8 |
| 61 | TAM | SAV | Sea | $ 89,788.52 | 757,822.7 |

*Figure 4: BAU scenario nodes used*

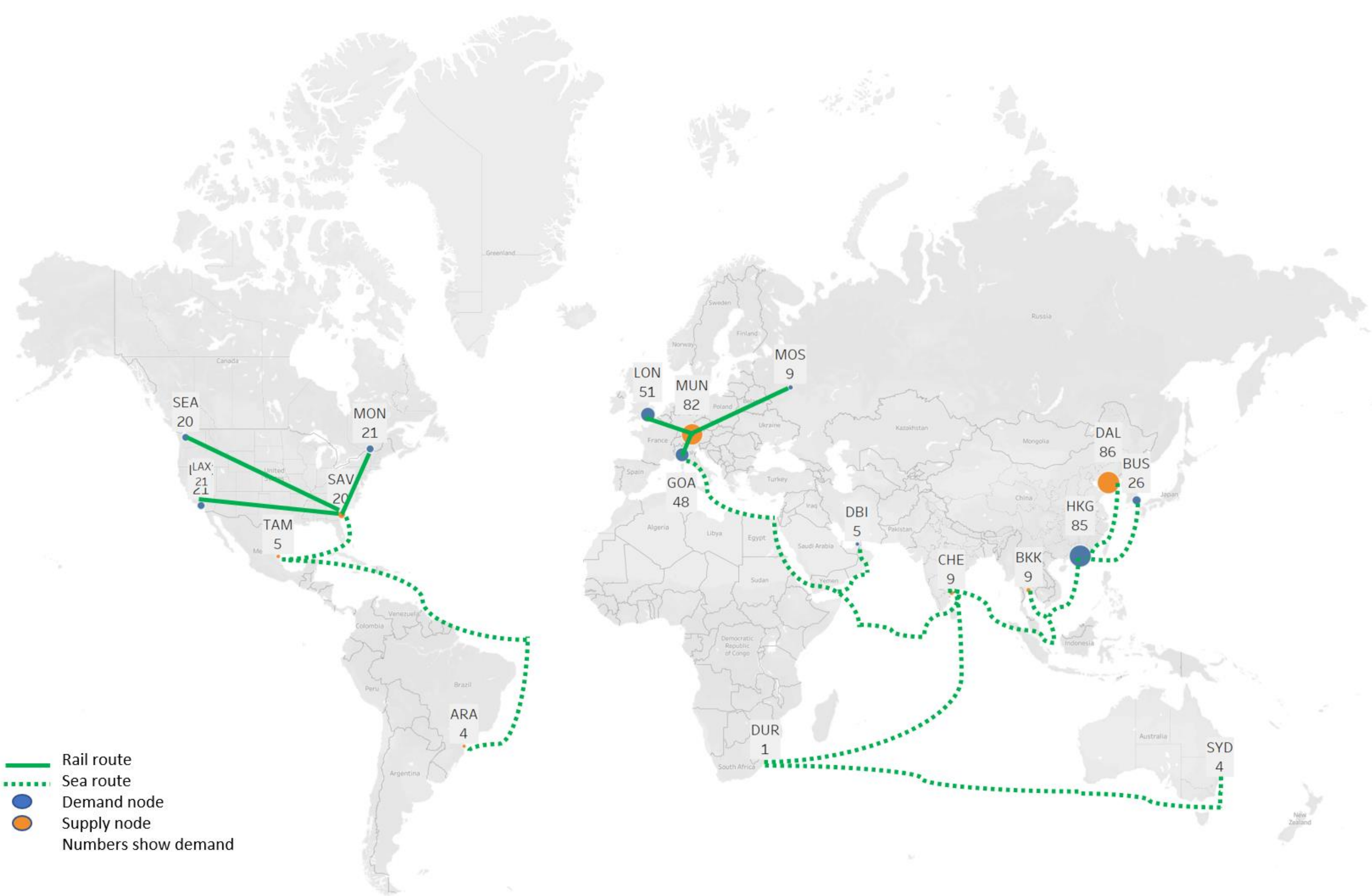


*Figure 5: BAU scenario (Map: © Mapbox and Openstreetmap)*

In the BAU scenario, all cars for Europe are made by Munich, all cars from Americas are made primarily by Tampico with Savannah building the remainder, all cars for China are made by Dalian, and cars for the rest of the world are made by either Durban or Munich. This results in a total cost of $13.371 billion ($26,425 per car) with total emissions of 444,601t-$CO_2$e (878.7 per car).

Now, five variations of the model will calculate the optimal paths for different scenarios. There will be a scenario for the lowest cost, a scenario for the lowest emissions, and three scenarios with varied weightings: equal balance between cost and emissions, a lower-cost weighting, and a lower-emissions weighting.

The total cost and emissions results are given below.

| Scenario | BAU | Lowest cost | Lower cost | Balanced | Lower emissions | Lowest emissions |
|---|---|---|---|---|---|---|
| Emissions weighting (w) | 0.5 | 0.5 | 0.33 | 0.5 | 0.66 | 1 |
| Total cost | $ 13,370,925,772.48 | $ 13,017,144,170.12 | $ 13,065,986,318.54 | $ 13,235,347,352.90 | $ 13,238,631,123.41 | $ 13,280,158,921.39 |
| -per car | $ 26,424.75 | $ 25,725.58 | $ 25,822.11 | $ 26,156.81 | $ 26,163.30 | $ 26,245.37 |
| Total emissions | 444,600,829.0 | 640,032,794.7 | 451,885,651.7 | 214,919,117.6 | 211,855,868.1 | 205,012,285.3 |
| -per car | 878.6577649 | 1264.886946 | 893.0546476 | 424.7413391 | 418.6874863 | 405.1626193 |
| Total weighted cost | 6,907,763,300.76 | 13,017,144,170.12 | 8,861,286,096.25 | 6,725,133,235.23 | 4,640,959,454.88 | 205,012,285.34 |

*Figure 6: Model scenario comparison table*

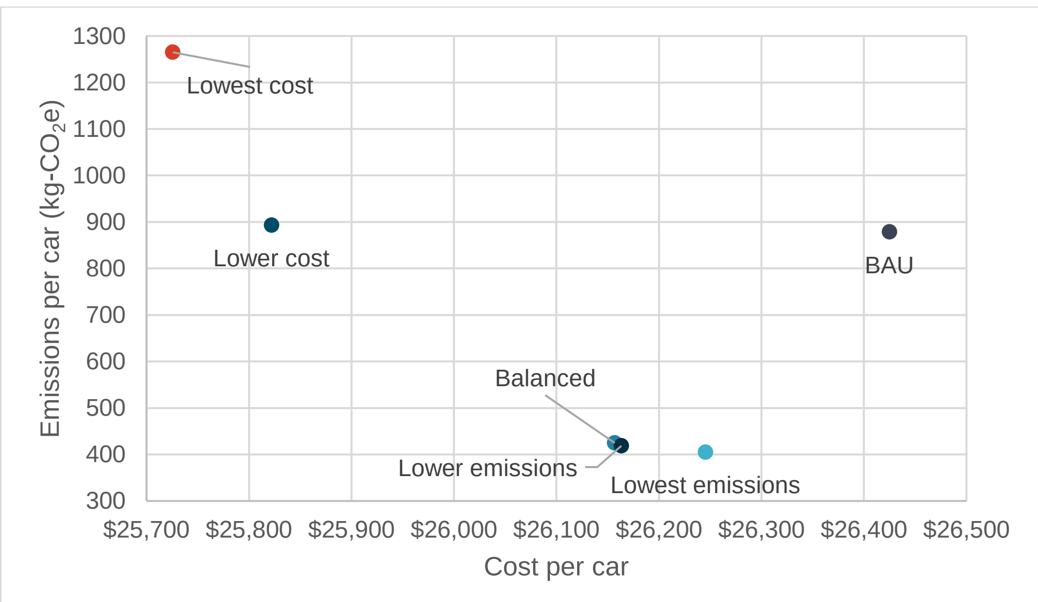


*Figure 7: Model scenario comparison chart*

When comparing to the BAU scenario, it appears that optimising through linear programming can bring strong benefits in both cost and emissions reduction. In terms of cost, any scenario works out cheaper than BAU; even the most aggressive emissions reduction would still work out cheaper than BAU. Logistics can even be optimised to significantly reduce the cost, however going too aggressively would raise emissions significantly, which would not be acceptable.

In terms of sensitivity, the model is more sensitive to $CO_2$ emissions than cost. Cost can only be reduced by 2.0% when comparing the maximum cost weight to the maximum emissions weight. On the other hand, the maximum emissions weight can reduce emissions by 212.2%. Versus the BAU, cost can be reduced by up to 2.7%, whereas $CO_2$ can be reduced by up to 116.9%.

Out of these scenarios, I would recommend the lowest emissions scenario, as it would still deliver cost reductions while reducing the greatest amount of $CO_2$ emissions.

| Units | Origin | Destination | Mode | Cost | Emissions |
|---|---|---|---|---|---|
| **189** | **Pro** | **MUN** | **Pro** | **$ 27,554,200.00** | **330,000.0** |
| **10** | **Pro** | **CHE** | **Pro** | **$ 25,048,600.00** | **330,000.0** |
| **10** | **Pro** | **BKK** | **Pro** | **$ 25,232,200.00** | **330,000.0** |
| **200** | **Pro** | **DAL** | **Pro** | **$ 25,228,600.00** | **330,000.0** |
| **70** | **Pro** | **TAM** | **Pro** | **$ 25,223,200.00** | **330,000.0** |
| **17** | **Pro** | **SAV** | **Pro** | **$ 26,305,000.00** | **330,000.0** |
| **5** | **Pro** | **ARA** | **Pro** | **$ 25,230,400.00** | **330,000.0** |
| **5** | **Pro** | **DUR** | **Pro** | **$ 25,282,600.00** | **330,000.0** |
| 1 | ARA | GOA | Sea | $ 255,229.08 | 2,154,155.1 |
| 1 | BKK | SYD | Sea | $ 259,606.50 | 2,191,100.9 |
| 1 | CHE | DBI | Sea | $ 106,783.19 | 901,259.2 |
| 26 | DAL | BUS | Sea | $ 27,011.23 | 227,977.1 |
| 85 | DAL | HKG | Rail | $ 305,698.11 | 74,081.3 |
| 3 | DAL | SYD | Sea | $ 269,571.56 | 2,275,206.8 |
| 4 | DUR | DBI | Sea | $ 194,254.26 | 1,639,522.4 |
| 47 | MUN | GOA | Rail | $ 47,482.09 | 11,506.6 |
| 51 | MUN | LON | Rail | $ 94,037.19 | 22,788.5 |
| 9 | MUN | MOS | Rail | $ 243,178.32 | 58,930.6 |
| 21 | SAV | MON | Rail | $ 192,503.29 | 46,650.2 |
| 20 | SAV | SEA | Rail | $ 482,545.70 | 116,937.6 |
| 21 | TAM | LAX | Rail | $ 319,499.85 | 77,425.9 |
| 44 | TAM | SAV | Rail | $ 267,897.84 | 64,921.0 |

*Figure 8: Lowest emissions scenario nodes used*

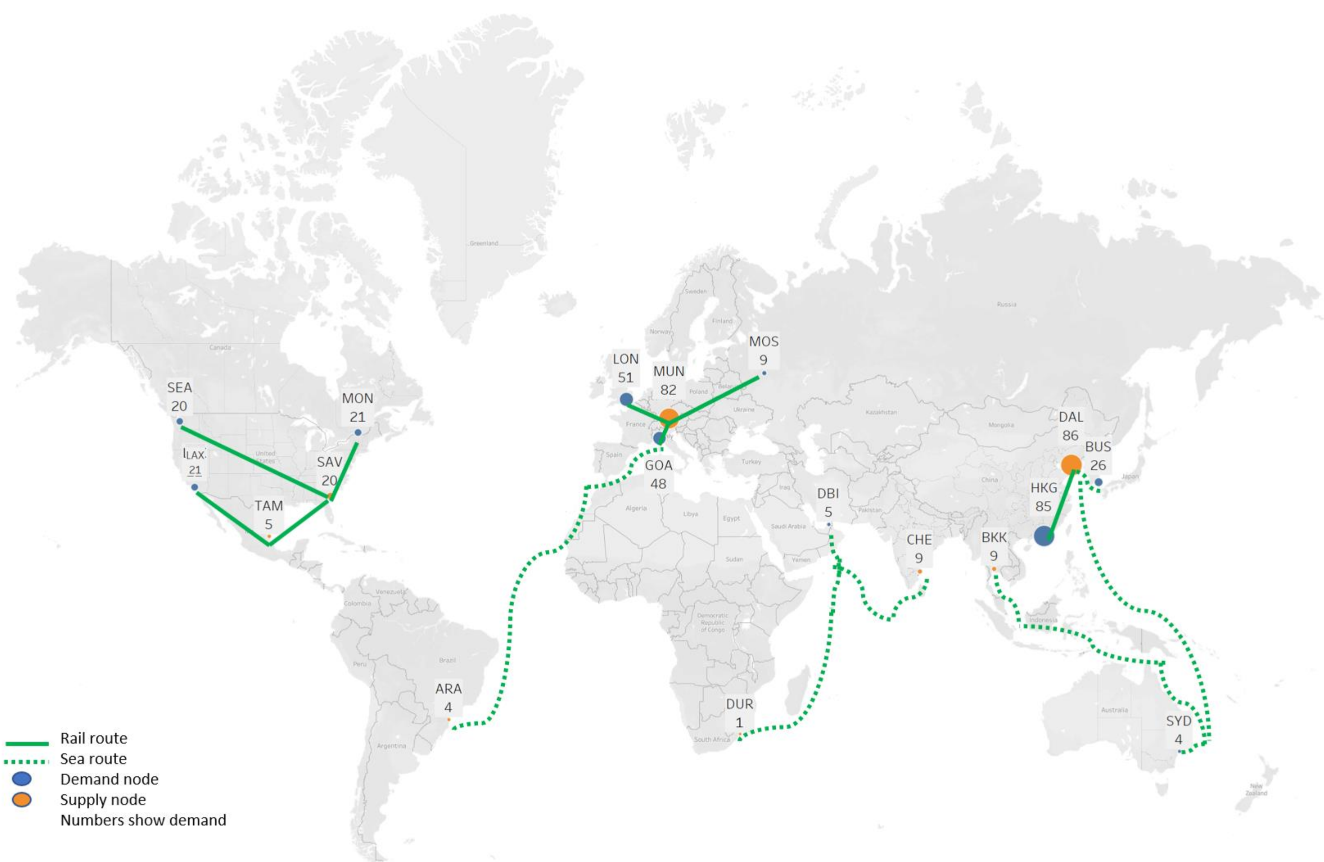


*Figure 9: Lowest emissions scenario (Map: © Mapbox and Openstreetmap)*

The manufacturing allocation and routes given above provide the strongest possible reduction of emissions. Shipping is generally made more local. Dalian now provides all stock of cars for Busan. Sydney receives all shipments from Asia as opposed to South Africa. Rail is also favoured where it is feasible, supporting broader trends in logistics (ESCAP, 2021); shipments from Dalian to Hong Kong are now performed by rail, as is all stock for Central and North America.

Also notable is that the Chennai, Bangkok, and Tampico plants are assigned to full capacity, whereas Durban and Araquari are assigned the minimum possible. Increasing capacities at these plants may deliver improved efficiency in the future. This model could be adapted to find the optimal allocation of resources to production to facilities and even where to place new factories. For example, adjusting the model so that the maximum production is 506 shows that production can be increased in Chennai, Bangkok and Tampico, and production closed in Durban and Savannah, to bring greater efficiency in both $CO_2$ emissions and cost. Another idea for future models would be to introduce constraints to either the total cost or total $CO_2$ emissions to ensure the maximum reduction possible in one target whilst ensuring the other target is not reduced (e.g. minimise $CO_2$ emissions subject to cost equal to or less than last year).

For details on all model scenarios, please refer to the spreadsheet.

## Conclusion

Prescriptive analytics are a powerful tool that allow managers to make decisions based on evidence and data. In particular, resolving network problems using linear programming can make significant contributions to supply chain management and logistics management. This has reached greater importance in modern times where sustainability has become an important issue in business (Rafi, 2022). While businesses have traditionally focused solely on reducing costs in logistics, now reducing carbon dioxide emissions have risen in importance.

This model mainly covers the distribution side of the automotive supply chain. It would be possible to expand the scope to cover more aspects of the supply chain. The model could also be modified in the future to support further ways to reduce financial and environmental costs, for example being adapted to predict where to build manufacturing plants. This model, like all models, is also only as good as its inputs (Segal, 2022). The data used in this report is based on estimates, and more detailed first-hand data would allow for a more detailed and accurate model.

Overall, the model created here demonstrates that it is possible to factor emissions into optimisation models to find the optimum production allocation and distribution network with both optimal financial cost and lower emissions. Companies involved in supply chain management and logistics management could expand their use of prescriptive analytics in ways like these to reduce their environmental footprint and help combat climate change.

# APPENDICES

## 1. Basis of Estimates of Costs for MM's Global Network

The München Motoren (MM) Class 3 car used in this scenario is based on the BMW 3 Series car. Data for the demand and costs of the Class 3 are based on data in the BMW Group Report 2021 (BMW Group, 2021).

**BMW GROUP VEHICLE PLANTS**

| Location | Country | Production programme 2021 | Electrification portfolio |
|---|---|---|---|
| Araquari | Brazil | BMW 3 Series, BMW X1, BMW X3, BMW X4, BMW X5 | |
| Berlin | Germany | BMW motorcycles | BEV |
| Chennai | India | BMW 2 Series, BMW 3 Series, BMW 5 Series, BMW 6 Series, BMW 7 Series, BMW X1, BMW X3, BMW X4, BMW X5, BMW X7, MINI Countryman | |
| Dingolfing | Germany | BMW 3 Series, BMW 4 Series, BMW 5 Series, BMW 6 Series, BMW 7 Series, BMW 8 Series, BMW M; BMW iX | BEV, PHEV |
| Leipzig | Germany | BMW 1 Series, BMW 2 Series, BMW i3, BMW M | BEV, PHEV |
| Manaus | Brazil | BMW motorcycles | |
| Munich | Germany | BMW 3 Series, BMW 4 Series, BMW i4, BMW M | BEV, PHEV |
| Oxford | United Kingdom | MINI, MINI Clubman, MINI Cooper SE* | BEV |
| Rayong | Thailand | BMW 2 Series, BMW 3 Series, BMW 5 Series, BMW 7 Series, BMW X1, BMW X3, BMW X5, BMW X7 BMW motorcycles | PHEV |
| Regensburg | Germany | BMW 1 Series, BMW 2 Series, BMW X1, BMW X2 | PHEV |
| Rosslyn | South Africa | BMW X3 | |
| San Luis Potosí | Mexico | BMW 2 Series, BMW 3 Series | PHEV |
| Spartanburg | USA | BMW X3, BMW X4, BMW X5, BMW X6, BMW X7, BMW M | PHEV |
| Rolls-Royce Manufacturing Plant, Goodwood | United Kingdom | Rolls-Royce Cullinan, Dawn, Ghost, Phantom, Wraith | BEV from 2023 |

*Figure 10: BMW Group vehicle plant list (BMW Group, 2021, p. 68)*

**BMW GROUP AUTOMOBILE PRODUCTION BY PLANT**

| in units | 2021 | 2020 | Change in % |
|---|---|---|---|
| Spartanburg | 433,810 | 361,365 | 20.0 |
| Dingolfing | 244,734 | 231,970 | 5.5 |
| Regensburg | 183,485 | 199,991 | – 8.3 |
| Leipzig | 191,604 | 200,968 | – 4.7 |
| Oxford | 186,883 | 175,984 | 6.2 |
| Munich | 151,154 | 143,758 | 5.1 |
| Rosslyn | 61,580 | 50,760 | 21.3 |
| Rayong | 24,624 | 25,752 | – 4.4 |
| Chennai | 8,472 | 6,228 | 36.0 |
| Araquari | 10,104 | 8,400 | 20.3 |
| Goodwood | 5,912 | 3,776 | 56.6 |
| San Luis Potosí | 69,149 | 56,081 | 23.3 |
| Tiexi (BBA)[2] | 335,311 | 311,137 | 7.8 |
| Dadong (BBA)[2] | 365,466 | 291,798 | 25.2 |
| Born (VDL Nedcar)[3] | 105,214 | 125,666 | – 16.3 |
| Graz (Magna Steyr)[3] | 54,547 | 35,747 | 52.6 |
| Partner plants | 29,220 | 26,256 | 11.3 |
| **Total** | **2,461,269** | **2,255,637** | **9.1** |

*Figure 11: BMW Group vehicle production by plant (BMW Group, 2021, p. 69)*

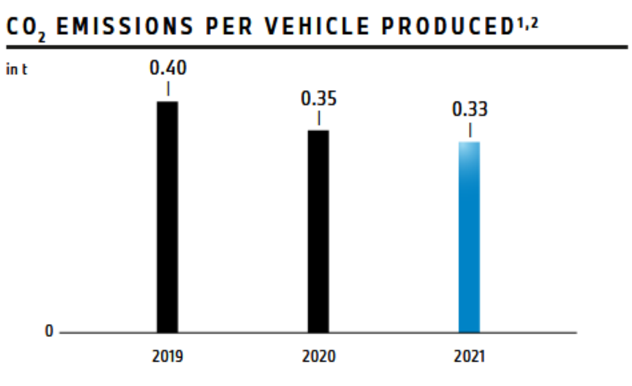


*Figure 12: BMW Group $CO_2$ emissions per vehicle produced (BMW Group, 2021, p. 74)*

**BMW GROUP DELIVERIES OF VEHICLES BY REGION AND MARKET [2]**

| in 1,000 units | 2021 | 2020 | 2019 | 2018 | 2017 |
|---|---|---|---|---|---|
| Europe | 949.1 | 913.6 | 1,081.6 | 1,097.4 | 1,101.9 |
| thereof Germany | 266.8 | 285.0 | 330.5 | 310.6 | 296.5 |
| thereof UK | 164.3 | 163.2 | 233.8 | 236.8 | 242.4 |
| Americas | 451.7 | 379.7 | 472.9 | 457.1 | 456.1 |
| thereof USA | 368.0 | 307.9 | 375.7 | 355.4 | 358.8 |
| Asia[1] | 1,067.9 | 986.5 | 930.8 | 871.8 | 847.7 |
| thereof China[1] | 847.9 | 778.4 | 724.7 | 635.8 | 595.0 |
| Other markets | 52.8 | 45.4 | 52.2 | 59.9 | 59.3 |
| **Total[1]** | **2,521.5** | **2,325.2** | **2,537.5** | **2,486.1** | **2,465.0** |

[1] Including the joint venture BMW Brilliance Automotive Ltd., Shenyang (2019: 538,612 units; 2018: 455,581 units; 2017: 385,705 units).
[2] Retail vehicle delivery data presented for 2020 and 2021 is not directly comparable to such data presented for previous years. For further information on retail vehicle delivery data, please see ↗ Comparison of Forecasts with Actual Outcomes.
[3] ↗ Consumption and carbon emissions.

*Figure 13: BMW Group deliveries by region and market (BMW Group, 2021, p. 110)*

**BMW GROUP — LARGEST AUTOMOBILE MARKETS 2021**

as a percentage of sales volume

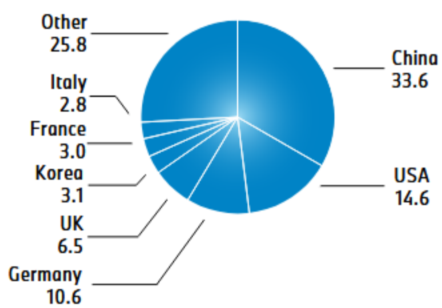


*Figure 14: BMW Group largest markets (BMW Group, 2021, p. 110)*

**DELIVERIES OF BMW VEHICLES BY MODEL VARIANT**[1,2]

| in units | 2021 | 2020 | Change in % | Share of BMW deliveries 2021 in % |
|---|---|---|---|---|
| BMW 1 Series / BMW 2 Series | 265,964 | 268,915 | – 1.1 | 12.0 |
| BMW 3 Series / BMW 4 Series | 490,969 | 420,295 | 16.8 | 22.2 |
| BMW 5 Series / BMW 6 Series | 326,212 | 322,457 | 1.2 | 14.7 |
| BMW 7 Series / BMW 8 Series | 62,628 | 66,728 | – 6.1 | 2.8 |
| BMW Z4 | 14,778 | 14,982 | – 1.4 | 0.7 |
| BMW X1 / X2 | 311,928 | 304,270 | 2.5 | 14.1 |
| BMW X3 / X4 | 414,671 | 347,565 | 19.3 | 18.7 |
| BMW X5 / X6 | 240,504 | 206,774 | 16.3 | 10.9 |
| BMW X7 | 54,957 | 48,693 | 12.9 | 2.5 |
| BMW i (iX, i3 and i8) | 31,179 | 28,162 | 10.7 | 1.4 |
| **BMW total** | **2,213,790** | **2,028,841** | **9.1** | **100.0** |

[1] ↗ Consumption and carbon emissions data
[2] Including the joint venture BMW Brilliance Automotive Ltd., Shenyang (2021: 651,236 units, 2020: 602,247 units).

*Figure 15: Deliveries of BMW vehicles by model (BMW Group, 2021, p. 111)*

Costs for labour are based on figures provided in James (2023). It was adjusted based on minimum wage data from WageIndicator (2023) as well as (BusinessTech, 2022), (Charoensuthipan, 2019), (U.S. Department of Labor, 2023) and (Agência Brasil, 2022).

## 2. Shipping Distances and Costs Between Nodes

The distances for the rail and sea routes were calculated using freight route planner Fluent Cargo (Fluent Cargo, 2023)

| Distance (sea) | MUN | CHE | BKK | DAL | TAM | SAV | ARA | DUR | GOA | LON | MOS | HKG | BUS | LAX | SEA | MON | SYD | DBI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MUN | X | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| CHE | N | X | 5172 | N | N | N | N | 8631 | 10525 | N | N | N | N | N | N | N | 10666 | 4147 |
| BKK | N | 5172 | X | N | N | N | N | N | N | N | N | 2741 | N | 14911 | N | N | 10082 | N |
| DAL | N | N | N | X | N | N | N | N | N | N | N | 3127 | 1049 | N | N | N | 10469 | N |
| TAM | N | N | N | N | X | 3487 | 12972 | N | 11119 | 10390 | N | N | N | N | N | N | N | N |
| SAV | N | N | N | N | 3487 | X | 10214 | N | N | 6901 | N | N | N | X | N | 4087 | N | N |
| ARA | N | N | N | N | 12972 | 10214 | X | N | 9912 | 11106 | N | N | N | N | N | N | N | N |
| DUR | N | 8631 | N | N | N | N | N | X | 13575 | N | N | N | N | N | N | N | 13955 | 7544 |
| GOA | N | 10525 | N | N | 11119 | N | 9912 | 13575 | X | 4219 | N | N | N | N | N | N | N | 8229 |
| LON | N | N | N | N | 10390 | 6901 | 11106 | N | 4219 | X | N | N | N | N | N | 6810 | N | N |
| MOS | N | N | N | N | N | N | N | N | N | N | X | N | N | N | N | N | N | N |
| HKG | N | N | 2741 | 3127 | N | N | N | N | N | N | N | X | 2219 | 12556 | N | N | N | N |
| BUS | N | N | N | 1049 | N | N | N | N | N | N | N | 2219 | X | 10237 | 9264 | N | N | N |
| LAX | N | N | 14911 | N | N | X | N | N | N | N | N | 12556 | 10237 | X | 2315 | N | 13280 | N |
| SEA | N | N | N | N | N | N | N | N | N | N | N | N | 9264 | 2315 | X | N | N | N |
| MON | N | N | N | N | N | 4087 | N | N | N | 6810 | N | N | N | N | N | X | N | N |
| SYD | N | 10666 | 10082 | 10469 | N | N | N | 13955 | N | N | N | N | N | 13280 | N | N | X | N |
| DBI | N | 4147 | N | N | N | N | N | 7544 | 8229 | N | N | N | N | N | N | N | N | X |

| Distance (rail) | MUN | CHE | BKK | DAL | TAM | SAV | ARA | DUR | GOA | LON | MOS | HKG | BUS | LAX | SEA | MON | SYD | DBI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MUN | X | N | N | N | N | N | N | N | 461 | 913 | 2361 | N | N | N | N | N | N | N |
| CHE | N | X | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| BKK | N | N | X | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| DAL | N | N | N | X | N | N | N | N | N | N | 8195 | 2968 | N | N | N | N | N | N |
| TAM | N | N | N | N | X | 2601 | N | N | N | N | N | N | N | 3102 | N | N | N | N |
| SAV | N | N | N | N | 2601 | X | N | N | N | N | N | N | N | 3894 | 4685 | 1869 | N | N |
| ARA | N | N | N | N | N | N | X | N | N | N | N | N | N | N | N | N | N | N |
| DUR | N | N | N | N | N | N | N | X | N | N | N | N | N | N | N | N | N | N |
| GOA | 461 | N | N | N | N | N | N | N | X | 1033 | N | N | N | N | N | N | N | N |
| LON | 913 | N | N | N | N | N | N | N | 1033 | X | N | N | N | N | N | N | N | N |
| MOS | 2361 | N | N | 8195 | N | N | N | N | N | N | X | N | N | N | N | N | N | N |
| HKG | N | N | N | 2968 | N | N | N | N | N | N | N | X | N | N | N | N | N | N |
| BUS | N | N | N | N | N | N | N | N | N | N | N | N | X | N | N | N | N | N |
| LAX | N | N | N | N | 3102 | 3894 | N | N | N | N | N | N | N | X | 1827 | 4575 | N | N |
| SEA | N | N | N | N | N | 4685 | N | N | N | N | N | N | N | 1827 | X | 4732 | N | N |
| MON | N | N | N | N | N | 1869 | N | N | N | N | N | N | N | 4575 | 4732 | X | N | N |
| SYD | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | X | N |
| DBI | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | X |

*Figure 16: Shipping route distances*

The rate per tonne-kilometre uses averages based on data by Ark Investment Management (2017). $CO_2$ per tonne-kilometre uses average data from the European Environment Agency (European Environment Agency, 2017).

| | | | | |
|---|---|---|---|---|
| Sea | Rate | Tons per 1000 units | Cost | |
| Rate | 0.016 | 1600 | 25.75 | $ per tonne-km |
| Emissions | 135.83 | 1600 | 217.328 | kgCO2e per tonne-km |
| Rail | Rate | Tons per 1000 units | Cost | |
| Rate | 0.064 | 1600 | 103.00 | $ per tonne-km |
| Emissions | 15.6 | 1600 | 24.96 | kgCO2e per tonne-km |

*Figure 17: Cost (rates and emissions) of shipping per ton-km*

The date here is in the spreadsheet under the “Data” tab. All monetary figures in this document use USD.

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