DHL Supply Chain Report

Minimum Carbon Emission Strategy (Production and Transportation)

Industrial Engineering 162: Linear Programming and Network Flows

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Table of Contents

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1. Executive Summary

DHL Supply Chain is a logistics and operations company which recognizes environmental protection as a responsibility, based on the ‘Go Green’ sustainability program initiated by the parent firm, Deutsche Post DHL. Going forward, DHL Supply Chain is committed to resolving carbon emission problems by improving carbon dioxide (CO2) efficiency across global operations by 30% compared to 2007 numbers.

DHL Supply Chain has been assigned the responsibility of shipping 920,000 LCD42” and 530,000 LCD32” TV units of a consumer electronics company, under a CNY 3 billion budget. The shipping is from seven original design manufacturers (ODMs) in Taiwan and China to the distribution center (DC) in Shanghai. ODMs 1 and 2 produce both LCD TV sets, the rest exclusively produce LCD42”, and each ODM has a TV unit production cost. Maximum individual ODM production of an LCD TV set is capped at 600,000 units to mitigate ODM dependency risk.

Seven transportation modes from ODMs to the DC are available: regular air, air express, road, road LTL (less than truckload), road network, rail, and water. Exceptions include ODM5 only shipping via road methods, and ODM6 only shipping via air or water. To maintain satisfactory inventory levels, there are minimum unit constraints for each shipping method (except water). Additionally, each shipping method has an associated shipping cost and carbon emission rate.

DHL Supply Chain wants to fulfill this operation within the budget and production constraints, while primarily minimizing CO2 emissions which depend on weight and distance shipped. Factoring in tax incentive and brand value, the budget could increase to CNY 3.3 billion which allows further evaluations of potential CO2 emission reductions through an increased budget.

After devising and optimizing a model for DHL Supply Chain's shipment network, our team has come to a set of recommendations to minimize CO2 emissions within all order demands. Upon additional research, our team analyzed the changes occurring with a potential CNY 3.3 billion budget. Furthermore, we have studied multiple ways in which modified demands, environmentally friendly shipping methods, and cheaper transportation/production costs can further minimize CO2 emissions. We will expand upon our findings in the following sections.

2. Results

2.1 Recommendation - Optimal Solution

Minimum CO2 emission:

The CO2 emission (kg) is calculated by multiplying the CO2 emission (kg per Ton-km) by distance and weight of each shipment. Within the current constraints and CNY 3B budget, the minimum CO2 emission for this operation is **7,401,248 kg.** Through an increase to a CNY 3.3B budget, the minimum CO2 emission decreases to **3,406,266 kg**. We notice that increasing the supply chain budget by 10% drastically reduces CO2 emissions by nearly half.

To achieve the optimal CO2 emission with a CNY 3B budget, we recommend utilizing ODM1 for production of both TV sets, while using ODM4 for further production of LCD42". To contrast, the optimal CO_2 emission with a CNY 3.3B budget is met via ODMs 4,5, and 7 for the LCD42” production alongside ODMs 1 and 2 for the LCD32” production. Both budgets primarily use regular air, road-network, rail, and water shipping methods. Our recommendation is summarized in Tables 1 and 2 for each budget respectively. Kindly note that the units produced for all other Product-ODM-Shipping iterations in Tables 1 and 2 are 0.

Table 1 - Optimal Solution, CNY 3B Budget

Product-ODM	Shipping Method	Units Produced (CNY 3B)
LCD42” ODM1	Road-Network	90,306
LCD42” ODM1	Water	229,694
LCD42” ODM4	Regular Air	46,000
LCD42” ODM4	Road-Network	1,694
LCD42” ODM4	Rail	138,000
LCD42” ODM4	Water	414,306
LCD32” ODM1	Regular Air	53,000
LCD32” ODM1	Road-Network	79,500
LCD32” ODM1	Rail	79,500
LCD32” ODM1	Water	318,000

Table 2 - Optimal Solution, CNY 3.3B Budget

Product-ODM	Shipping Method	Units Produced (CNY 3.3B)
LCD42” ODM4	Water	228,000
LCD42” ODM5	Road-Network	92,000
LCD42” ODM7	Regular Air	46,000
LCD42” ODM7	Rail	138,000
LCD42” ODM7	Water	416,000
LCD32” ODM1	Water	257,625
LCD32” ODM2	Regular Air	53,000
LCD32” ODM2	Road-Network	79,500
LCD32” ODM2	Rail	79,500
LCD32” ODM2	Water	60,375

Explanation and Analysis:

To meet the CNY 3B demand, our optimal solution prioritized ODMs with cheaper shipping and TV unit production costs. Therefore, our recommendation which included ODMs 1 and 4 was cost-oriented. ODM1 was the cheapest option for LCD32” manufacturing, so the entire LCD32” production was allocated to ODM1. Additionally, ODM4 was the cheapest option for LCD42” manufacturing, which meant that ODM4 was allocated the maximum possible production (600,000 units). The remaining required units were allocated to the second cheapest LCD42” manufacturing option, ODM1. Our findings are summarized in **Table 3.**

Despite being the cheapest options, ODMs 1 and 4 were the furthest ODMs from the DC. This meant that the additional distance contributed to higher carbon emissions. If the budget was increased to the possible CNY 3.3B, then this added budget would be used for more expensive but more environmental ODM options. Therefore, our optimal solution for the CNY 3.3B scenario featured ODMs 1,2,4,5, and 7 as displayed in **Table 3.** These ODMs offer an optimal cost-carbon emission balance, whereas ODMs 3 and 6 were far more expensive than LCD42”-exclusive ODMs to be in our recommendation. A key takeaway is that increasing the supply chain budget factors into utilizing environmentally-friendly ODMs, which would severely reduce carbon emissions from about 7.4M kg to 3.4M kg, roughly a 54% decrease.

Table 3 (Production per ODM)

ODM	Units Produced (CNY 3B budget)	Units Produced (CNY (3.3B budget)
1	320,000 (LCD42”), 530,000 (LCD32”)	257,625 (LCD32”)
2	0	272,375 (LCD32”)
3	0	0
4	600,000 (LCD42”)	228,000 (LCD42”)
5	0	92,000 (LCD42”)
6	0	0
7	0	600,000 (LCD42”)

Table 4 (Units per used shipping method)

Shipping Method	Units Shipped (CNY 3B budget)	Units Shipped (CNY 3.3B budget)
Regular Air	46,000 (LCD42”) 53,000 (LCD32”)	46,000 (LCD42”) 53,000 (LCD32”)
Road Network	92,000 (LCD42”) 79,500 (LCD32”)	92,000 (LCD42”) 79,500 (LCD32”)
Rail	138,000 (LCD42”) 79,500 (LCD32”)	138,000 (LCD42”) 79,500 (LCD32”)
Water	644,000 (LCD42”) 318,000 (LCD32”)	644,000 (LCD42”) 318,000 (LCD32”)

Our primary objective is to minimize CO2 emissions. Looking at the CO2 emission associated with each shipping method, we notice that water shipment has the lowest emissions and is the most sustainable transportation. As such, the optimal shipping strategy to reduce carbon emissions while maintaining demands is water-oriented. We recommend reaching the minimum demand for each required shipping method, and then to ship all remaining units via water as illustrated in **Table 4** (shipping methods not included have 0 units shipped). If a shipping demand pertains to more than one method (i.e regular air or air express), we opted for the cheaper shipping method. The budget alternatives do not factor into the shipping strategy, as both budget options have the exact same optimal shipping recommendations.

2.2 Sensitivity Analysis

Through sensitivity analysis, we can see how much different parameters of the model can be changed without affecting the basis, which is the set of all product-ODM-shipping combination with units greater than 0 (i.e. the product-ODM-shipping combinations listed in Tables 1 and 2 for the CNY 3 billion and CNY 3.3 billion budgets respectively). It is important to maintain the basis as the parameters of the situation are likely to fluctuate and change the situation and we want to ensure that the solution can adapt with these changes without sacrificing contracts with ODMs or shipping companies, possibly resulting in financial penalties and bad will. This analysis was done at both the CNY 3 billion and CNY 3.3 billion budgets to give a complete comparison for both if DHL is able to secure the budget increase or not. This also will give a better picture of other consequences of reformulating shipping around CO2 emission.

Change of CO2 Emissions:

First, we will look at changing the carbon cost per unit shipped via each product-ODM-shipping combination while still maintaining the basis. Below is **Table 5** describing the minimum and maximum carbon dioxide cost (in kg) for each combination without affecting the basis. Please note that the abbreviations that in the table, the shipping methods Regular Air, Air Express, and Road Network are written as Reg. Air, Air Exp., and Road-Net respectively.

Table 5 (Carbon Emission (Emis.) Per Unit Shipped)

ODM	Shipping Method	Min Emis. CNY 3B	Current Emis. CNY 3B	Max Emis. CNY 3B	Min Emis. CNY 3.3B	Current Emis. CNY 3.3B	Max Emis. CNY 3.3B
1 42"	Reg. Air	68.1671	79.4534	Inf	22.5029	79.4534	Inf
1 42"	Air Exp.	61.0394	79.4534	Inf	22.412	79.4534	Inf
1 42"	Road	1.88545	3.38229	Inf	0.542619	3.38229	Inf
1 42"	Road LTL	2.95462	3.38229	Inf	0.556246	3.38229	Inf
1 42"	Road-Net.	3.35259	3.38229	Inf	0.561697	3.38229	Inf
1 42"	Rail	1.40318	1.57252	Inf	0.678151	1.57252	Inf
1 42"	Water	-2.60397	0.386232	Inf	0.326419	0.386232	Inf
2 42"	Reg. Air	-2.46873	49.199	Inf	21.6026	49.199	Inf
2 42"	Air Exp.	-15.2987	49.199	Inf	21.4391	49.199	Inf
2 42"	Road	-12.7261	2.09438	Inf	0.356391	2.09438	Inf
2 42"	Road LTL	-11.3005	2.09438	Inf	0.37456	2.09438	Inf
2 42"	Road-Net.	-11.1579	2.09438	Inf	0.376377	2.09438	Inf
2 42"	Rail	-13.9211	0.973731	Inf	0.482839	0.973731	Inf
2 42"	Water	-12.7997	0.239162	Inf	0.158361	0.239162	Inf
3 42"	Reg. Air	-4.73464	43.7184	Inf	21.5737	43.7184	Inf
3 42"	Air Exp.	-16.1391	43.7184	Inf	21.4284	43.7184	Inf
3 42"	Road	-29.2475	1.86107	Inf	0.14582	1.86107	Inf
3 42"	Road LTL	-27.822	1.86107	Inf	0.16399	1.86107	Inf
3 42"	Road-Net.	-27.6794	1.86107	Inf	0.165806	1.86107	Inf
3 42"	Rail	-30.4426	0.86526	Inf	0.272268	0.86526	Inf
3 42"	Water	-29.9627	0.21252	Inf	-0.06039	0.21252	Inf
4 42"	Reg. Air	-67.5254	68.112	Inf	22.5076	68.112	Inf
4 42"	Air Exp.	60.9842	68.112	Inf	22.4167	68.112	Inf

ODM	Shipping Method	Min Emis. CNY 3B	Current Emis. CNY 3B	Max Emis. CNY 3B	Min Emis. CNY 3.3B	Current Emis. CNY 3.3B	Max Emis. CNY 3.3B
4 42"	Road	1.83032	2.89949	Inf	0.5473	2.89949	Inf
4 42"	Road LTL	2.82821	2.89949	Inf	0.560018	2.89949	Inf
4 42"	Road-Net.	-Inf	2.89949	Inf	0.560927	2.89949	Inf
4 42"	Rail	-0.9519	1.34805	Inf	0.682832	1.34805	Inf
4 42"	Water	0.301649	0.3311	0.390913	0.196705	0.3311	0.390913
5 42"	Road	-38.5835	0.040458	Inf	0.026831	0.040458	Inf
5 42"	Road LTL	-37.8707	0.040458	Inf	0.035916	0.040458	Inf
5 42"	Road-Net.	-37.5143	0.040458	0.045	-0.21935	0.040458	0.045
6 42"	Reg. Air	-46.5314	21.8592	Inf	21.041	21.8592	Inf
6 42"	Air Exp.	-60.7869	21.8592	Inf	20.8593	21.8592	Inf
6 42"	Water	-36.2631	0.10626	Inf	-0.14069	0.10626	Inf
7 42"	Reg. Air	18.2666	21.7325	21.8687	-1.30882	21.7325	21.8687
7 42"	Air Exp.	7.57496	21.7325	Inf	21.5962	21.7325	Inf
7 42"	Road	-6.24625	0.92514	Inf	0.304583	0.92514	Inf
7 42"	Road LTL	-4.8207	0.92514	Inf	0.322752	0.92514	Inf
7 42"	Road-Net.	-4.53558	0.92514	Inf	0.326386	0.92514	Inf
7 42"	Rail	-7.51258	0.430122	0.587207	0.062038	0.430122	0.587207
7 42"	Water	-6.3912	0.105644	0.240039	-0.05144	0.105644	0.240039
8 32"	Reg. Air	-50.6027	59.5901	Inf	37.5587	59.5901	Inf
8 32"	Air Exp.	54.2442	59.5901	Inf	37.4906	59.5901	Inf
8 32"	Road	1.41409	2.53672	Inf	1.67972	2.53672	Inf
8 32"	Road LTL	2.21597	2.53672	Inf	1.68994	2.53672	Inf
8 32"	Road-Net.	-1.1537	2.53672	Inf	1.69403	2.53672	Inf
8 32"	Rail	-0.67258	1.17939	Inf	0.861041	1.17939	Inf
8 32"	Water	-Inf	0.289674	0.418821	0.263549	0.289674	0.418821
9 32"	Reg. Air	7.84827	36.8993	37.0219	-1.01843	36.8993	37.0219

ODM	Shipping Method	Min Emis. CNY 3B	Current Emis. CNY 3B	Max Emis. CNY 3B	Min Emis. CNY 3.3B	Current Emis. CNY 3.3B	Max Emis. CNY 3.3B
9 32"	Air Exp.	-1.77423	36.8993	Inf	36.7766	36.8993	Inf
9 32"	Road	-8.30945	1.57078	Inf	1.55579	1.57078	Inf
9 32"	Road LTL	-7.24029	1.57078	Inf	1.56942	1.57078	Inf
9 32"	Road-Net.	-7.13337	1.57078	1.57214	0.14803	1.57078	1.57214
9 32"	Rail	-9.07874	0.730298	1.04864	0.146667	0.730298	1.04864
9 32"	Water	-8.3647	0.179372	0.205497	0.050224	0.179372	0.205497

In **Table 5** many of the minimum emissions per unit are negative numbers. This means that the carbon emitted per unit at that row's product-ODM-shipping combination can decrease as small as possible without affecting the basis (so either remains a part of it or stays out of it) since shipping will never result in a net decrease in carbon emissions. Similarly, many of the maximum emissions per unit are infinite, so the carbon emissions of their product-ODM-shipping combination can increase unbounded without affecting the basis. The current numbers were calculated using a number of assumptions, including how much CO2 is emitted in kg per Ton-Km shipped, how heavy each product is, and how far the distance is from ODM to DC. These assumptions are not perfect; a more efficient fuel could be used, the distance via water might be longer than road, and each TV may have a slight variability in weight. What the non-negative and non-infinite bounds tell us is how much reality can deviate from our assumptions without needing to recalculate the entire problem.

Shadow Pricing:

Second, we will look at how much our constraints can change (e.g. how can the minimum number of units of LCD 42" shipped by rail change) without affecting the basis. From this, we can also see that if these constraints do change, how they affect CO2 emissions, these changes are represented as a change of CO2 emission per unit of product shipped and are referred to as shadow prices.

Total Demand:

Table 6 (Demand by TV Size, CNY 3.3B Budget)

TV Size	Shadow Price	Min. Demand	Current Demand	Max. Demand
42"	1.64179	898319	920000	925081
32"	1.48808	508287	530000	535557

Table 7 (Demand by TV Size, CNY 3B Budget)

TV Size	Shadow Price	Min. Demand	Current Demand	Max. Demand
42"	103.59	919626	920000	920007
32"	94.3174	529589	530000	530008

As described in **Table 6**, the total demand for each product given a CNY 3.3 billion budget can only decrease in demand by around 20,000 units or increase in demand by about 5,000 units without changing the basis. However, as the shadow prices for each of them is non-zero, changing the total demand will affect the total CO2 emission, and as both shadow prices are positive, increasing the demand for either will result in an increase in CO2 emission. Our recommendation is for DHL to reevaluate the demand to see if it is actually lower than first assessed to ensure that they are not unnecessarily increasing CO2 emissions by sending extra units, if they do have a CNY 3.3 billion budget. [MS1]

If DHL is unable to secure the extra funding, by **Table 7**, demand can only decrease by less than 500 for both products and increase by less than 10. As like before, the shadow prices are positive, so decreasing demand will result in a lowering of CO2 emissions. However, as the potential change in demand is so small (a 0.05% decrease in total product), the will only reduce the carbon emissions at most by 0.32% assuming that all the decrease in demand is taken from the most carbon expensive product-ODM-shipping combination for that product (ODM 1 Road-Network for the 42” and ODM 1 Regular Air for the 32”). We recommend that DHL does not reevaluate demand in this situation, as there is such little potential loss in CO2 emissions, and that the cost of reevaluating might potentially exceed the decreased cost from not producing excess product.

Maximum Demand Per ODM:

Table 8 (Maximum Units Shipped by Each ODM CNY 3.3B Budget)

ODM	Units Shipped	Shadow Price	Lowest Max Demand	Current Max Demand	Highest Max Demand
1 42"	0	0	0	600000	Inf
2 42"	0	0	0	600000	Inf
3 42"	0	0	0	600000	Inf
4 42"	228000	0	228000	600000	Inf
5 42"	92000	0	92000	600000	Inf
6 42"	0	0	0	600000	Inf
7 42"	600000	-0.1344	287938	600000	673132
1 32"	257625	0	257625	600000	Inf
2 32"	272375	0	272375	600000	Inf

By **Table 8**, the demands for the unused ODMs can increase or decrease without ever affecting our basis. This tells us that the maximum demand restriction has no bearing on whether or not these ODMs are used. ODM 7 produces at maximum capacity, and its negative shadow price (-0.1344) means that if the maximum units increased in ODM 7, there would be more units produced there (until max demand exceeds 673132) which would result in a decrease of CO_2 emissions. For this reason, we recommend DHL try to renegotiate contracts with ODM 7 to see if it is possible to increase the production there if they are able to secure the intended funds.

Table 9 (Maximum Units Shipped by Each ODM CNY 3B Budget)

ODM	Units Shipped	Shadow Price	Lowest Max Demand	Current Max Demand	Highest Max Demand
1 42"	113000	0	320000	600000	Inf
2 42"	0	0	0	600000	Inf
3 42"	0	0	0	600000	Inf
4 42"	600000	-0.42239	598027	600000	705160
5 42"	0	0	0	600000	Inf
6 42"	0	0	0	600000	Inf
7 42"	0	0	0	600000	Inf
1 32"	530000	0	530000	600000	Inf
2 32"	0	0	0	600000	Inf

Similarly for the CNY 3B budget, ODM 4 produces the maximum amount, 600,000 by **Table 9**, and has a negative shadow price (-0.42239), which would mean that like ODM 7 with the CNY 3.3B budget, increasing production at ODM 4 would decrease the CO2 emissions linearly by the extra number of units produced up until the highest maximum demand (673132).

Ship Method Requirements:

Table 10 (Units Required by Each Shipping Method)

Shipping Method	Current Units Shipped Requirement	Minimum Units Shipped Requirement (CNY 3.3B)	Maximum Units Shipped Requirement (CNY 3.3B)	Minimum Units Shipped Requirement (CNY 3B)	Maximum Units Shipped Requirement (CNY 3B)
Air (42”)	46000	25909.9	50708.1	45430.8	46010.7
Air (32”)	53000	29275.9	58090.9	52241.1	53014.2
Road (42”)	92000	40375.2	104098	75580.8	92376.5
Road (32”)	79500	0	126515	52742.8	80002
Rail (42”)	138000	0	290719	107898	138565
Rail (32”)	79500	0	126067	39364.1	80253

We find that the slack variable in all segments of both above cases are 0, indicating that these are all binding constraints in terms of CO2 output. This makes sense considering sea shipping is generally the cheapest and most carbon efficient method and we'd ship all of our product by sea if possible.

In addition, we find that in the 3.3 billion scenario, we are able to confine 32'' road and all rail shipping to individual ODM's (from the minimum requirement for which the model holds falling to 0), which would logically simplify organization.

Cost:

Table 11 (Budget Sensitivity CNY 3.3B Budget)

Minimum Budget	Current Budget	Max Budget	Shadow Price
3289610000	3300000000	3344320000	-0.000641203

Table 12 (Budget Sensitivity CNY 3B Budget)

Minimum Budget	Current Budget	Max Budget	Shadow Price
2999990000	3000000000	3000770000	-0.050309

Here we note that changing the budget doesn't do much to our optimal solution. The main changes being that the 3 billion CNY budget has a much tighter range for which the solution we found is optimal as compared to the 3.3 billion CNY budget.

We also find that that shadow price decreased by a factor of about 78 between the 3 and 3.3 billion budgets. This indicates that we are hitting diminishing returns, with additional budget increases above 3.3 billion having far less effect than the initial boost to 3.3 billion from 3 billion.

2.3 Additional Recommendations:

DHL should consider re-evaluating the problem with respect to time. One of the largest issues of this problem water is by far the cheapest and most carbon efficient method of shipping, so it is prioritized over all other forms of shipping. However, water is also the slowest method of shipping, so DHL should consider reformulating the problem to better take into account time in order to maintain a steady supply.

DHL should consider encouraging ODM 5,6 and 7 to open production of 32" screens. We suggest the investment of capital to potentially also open production of 32'' screens at ODM 5,6 and 7 (especially 7). This recommendation is primarily based on ODM 5, 6 and 7 being much closer to the distribution center than the others (6,7 being half as far as the current closest source of 32'' screens and 5 being 50 times closer) and the fact we already source large amounts of 42'' screens from ODM 7. An implementation of this suggestion at reasonable cost, as well as of others regarding general transportation and ODM 5, would allow DHL to reduce reliance on a single ODM and move 32'' screens at lower shipping rates over far shorter distances. DHL could move more items from ODM 7 to the distribution center and use the money saved to ship from more expensive, but closer ODMs 5 and 6.

DHL should look into ways to reduce CO2 for each shipping. While this would seem to be a relatively obvious path of inquiry due to the direct impact it would have on CO2 emissions, it could also be a path to more diversified shipping methods (and thus resistance to disruption in one particular ODM or shipping route). Currently, sea shipping is the best option due to it being slightly cheaper and enormously more carbon-efficient than any other source (4x more efficient than rail, the next closest for carbon per km). We currently only even use non-sea shipping purely to satisfy logistical needs from sea shipping being slow. An investment into low-carbon shipping (such as electrical vehicle fleets) could help us lower overall emissions, especially costs from routes like ODM 5 can be successfully reduced. Even if these cost reductions are not possible, a carbon efficiency increase would still help lower the emissions of the air, road and rail routes we must use by quota.

DHL must look into how to reduce cost for shipping via road for ODM 5. Nearly all of our extant shipping comes from very few ODMs by sea; which, while carbon-efficient, has problems not necessarily covered in the scope of this problem. To us, ODM 5 represents both an anomaly and a potential opportunity to further reduce our carbon impact. It is 20x closer to the distribution center than the next closest ODM, yet costs more than any other ODM for the same shipping method. We believe capital investment and research towards the reduction of this abnormally high shipping cost (whether by renegotiating road routes, buying more vehicles or other method) would do greatly to save the company money and further reduce carbon footprint. Even if cost improvements still do not directly allow it to compete with sea shipping, it will still represent the lowest carbon option of all ODMs/shipping methods.

3. Appendix

3.1 Model

Our team used AMPL, an algebraic modeling language commonly used to set up and solve high-complexity problems for large-scale mathematical computing, to compute and optimize the amount of carbon emissions reduction that can be gained from a 10% increase in DHL's shipping budget. We adjusted some of the outputs that were clearly rounding errors as they violated our constraints by fractions of a unit.

In our .dat file, we define the carbon footprint of each shipping method, distance from distribution center to each ODM and production cost for each item at each ODM in three lists. For simplicity, we considered the 32'' inch screen production lines at ODM 1 and 2 as separate ODMs, labeling them ODM 8 and 9.

Following this, we define a 2d array of all ODM's and their respective shipping costs by respective shipping methods in the form: ODM[j, i], with j representing ODM and i representing specific methods used to ship. Note that we also use j and i on the other 3 lists when referring to a specific ODM/shipping method.

Using these variables, we devise an objective function to calculate the total carbon emissions released for a specific shipping arrangement. This function (in simplified form, for ease of understanding) is as follows:

Carbon emissions = Sum of (0.022 tons respective carbon emissions * respective distances) for all shipping methods used in ODM 1-7 + Sum of (0.0165 tons* respective carbon emissions * respective distances) for all shipping methods used in ODM 8-9*

Along with this objective function, we also include constraints based on total demand for each screen size (42’’ or 32’’), maximum production at a single ODM, specific shipping quotas for air, road and rail and maximum budget.

An example of each type is given below:

Total demand for 42’’ screens:

$$\text{Total\_Demand\_42: } \sum_{j=1}^{7} \sum_{i=1}^{7} \text{ODM}_{ji} = 920000$$

Maximum production limit per ODM:

$$\text{Max\_Demand\_ODM } \{\text{j in 1..9}\}\text{: } \sum_{i=1}^{7} \text{ODM}_{ji} <= 600000;$$

This actually yields nine constraints, one for each j in 1 to 9.

Air shipping quota for 42’’ screens:

$$\text{Shipping\_Demand\_Air\_42: } \sum_{j=1}^{7} \sum_{i=1}^{2} \text{ODM}_{ji} >= 46000;$$

Cost:

$$\text{Cost: } \sum_{j=1}^{7} \sum_{i=1}^{2} (\mathit{Production\_cost}_{\mathrm{j}} + \mathit{Shipping\_cost}_{\mathrm{ji}}{*}0.022) * \text{ODM}_{ji}$$

$$+ \sum_{j=8}^{9} \sum_{i=1}^{2} (\mathit{Production\_cost}_{\mathrm{j}} + \mathit{Shipping\_cost}_{\mathrm{ji}}{*}0.0165) * \text{ODM}_{ji} <= 3300000000;$$

Note that the only thing that changes between different costs is whether the final value in cost is 3 billion or 3.3 billion.

After defining everything, we left the actual calculation to AMPL, which produced optimal solutions for both of our budget cases. In our case, the optimal solution represented the minimum amount of carbon dioxide emissions we could achieve at our given budget constraints, as defined by according to our objective function and associated other constraints. AMPL also yielded us the specific values of all our variables and constraints, as well as secondary information like slack variable value and shadow prices.

This auxiliary information allowed us to perform detailed sensitivity analysis on how specific segments of our shipping plan interacted with the whole, and provide recommendations towards future improvements of the system.

Output for CNY 3.3B Budget:

```
ampl: option solver cplex;
ampl: option cplex_options 'sensitivity';
ampl: option presolve 0;
ampl: model project.mod;
ampl: data project.dat;
ampl: solve;
CPLEX 12.10.0.0: sensitivity
CPLEX 12.10.0.0: optimal solution; objective 3406266.334
14 dual simplex iterations (0 in phase I)

suffix up OUT;
suffix down OUT;
suffix current OUT;
ampl: display _varname, _var, _var.rc, _var.down, _var.current, _var.up;
:     _varname      _var         _var.rc         _var.down     _var.current
 :=
1    'ODM[1,1]'       0       56.9506            22.5029      79.4534
2    'ODM[1,2]'       0       57.0414            22.412       79.4534
3    'ODM[1,3]'       0        2.83967            0.542619     3.38229
4    'ODM[1,4]'       0        2.82604            0.556246     3.38229
5    'ODM[1,5]'       0        2.82059            0.561697     3.38229
6    'ODM[1,6]'       0        0.894365           0.678151     1.57252
7    'ODM[1,7]'       0        0.0598128          0.326419     0.386232
8    'ODM[2,1]'       0       27.5964            21.6026      49.199
9    'ODM[2,2]'       0       27.76              21.4391      49.199
10   'ODM[2,3]'       0        1.73798            0.356391     2.09438
11   'ODM[2,4]'       0        1.71982            0.37456      2.09438
12   'ODM[2,5]'       0        1.718              0.376377     2.09438
13   'ODM[2,6]'       0        0.490892           0.482839     0.973731
14   'ODM[2,7]'       0        0.0808015          0.158361     0.239162
15   'ODM[3,1]'       0       22.1447            21.5737      43.7184
16   'ODM[3,2]'       0       22.29              21.4284      43.7184
17   'ODM[3,3]'       0        1.71525            0.14582      1.86107
18   'ODM[3,4]'       0        1.69708            0.16399      1.86107
19   'ODM[3,5]'       0        1.69526            0.165806     1.86107
20   'ODM[3,6]'       0        0.592992           0.272268     0.86526
21   'ODM[3,7]'       0        0.272907          -0.0603865    0.21252
22   'ODM[4,1]'       0       45.6044            22.5076      68.112
23   'ODM[4,2]'       0       45.6953            22.4167      68.112
24   'ODM[4,3]'       0        2.35219            0.5473       2.89949
25   'ODM[4,4]'       0        2.33947            0.560018     2.89949
26   'ODM[4,5]'       0        2.33856            0.560927     2.89949
27   'ODM[4,6]'       0        0.665218           0.682832     1.34805
28   'ODM[4,7]'  228000        0                  0.196705     0.3311
29   'ODM[5,1]'       0    46529.3           -46528.4          0.9504
30   'ODM[5,2]'       0    46529.3           -46528.4          0.9504
31   'ODM[5,3]'       0        0.0136268          0.0268312    0.040458
32   'ODM[5,4]'       0        0.00454228         0.0359157    0.040458
33   'ODM[5,5]'   92000        0                 -0.219348     0.040458
34   'ODM[5,6]'       0    46551.1           -46551            0.01881
35   'ODM[5,7]'       0    46551.4           -46551.4          0.00462
36   'ODM[6,1]'       0        0.818194          21.041       21.8592
37   'ODM[6,2]'       0        0.999885          20.8593      21.8592
38   'ODM[6,3]'       0    46552.1           -46551.1          0.930534
39   'ODM[6,4]'       0    46552.1           -46551.1          0.930534
40   'ODM[6,5]'       0    46552.1           -46551.1          0.930534
41   'ODM[6,6]'       0    46551.5           -46551            0.43263
42   'ODM[6,7]'       0        0.246947          -0.140687     0.10626
43   'ODM[7,1]'   46000       -8.88178e-16       -1.30882     21.7325
44   'ODM[7,2]'       0        0.136268          21.5962      21.7325
```

```
45   'ODM[7,3]'        0          0.620556          0.304583     0.92514
46   'ODM[7,4]'        0          0.602387          0.322752     0.92514
47   'ODM[7,5]'        0          0.598753          0.326386     0.92514
48   'ODM[7,6]'   138000          0                 0.0620381    0.430122
49   'ODM[7,7]'   416000          0                -0.385248     0.105644
50   'ODM[8,1]'        0         22.0313           37.5587      59.5901
51   'ODM[8,2]'        0         22.0995           37.4906      59.5901
52   'ODM[8,3]'        0          0.856995          1.67972      2.53672
53   'ODM[8,4]'        0          0.846775          1.68994      2.53672
54   'ODM[8,5]'        0          0.842687          1.69403      2.53672
55   'ODM[8,6]'        0          0.318346          0.861041     1.17939
56   'ODM[8,7]'   257625          0                 0.238078     0.289674
57   'ODM[9,1]'    53000          0                -1.01843     36.8993
58   'ODM[9,2]'        0          0.122642         36.7766      36.8993
59   'ODM[9,3]'        0          0.0149895         1.55579      1.57078
60   'ODM[9,4]'        0          0.00136268        1.56942      1.57078
61   'ODM[9,5]'    79500          0                 0.14803      1.57078
62   'ODM[9,6]'    79500          2.22045e-16       0.146667     0.730298
63   'ODM[9,7]'    60374.5        0                 0.050224     0.179372
;
:      _var.up       :=
1    1e+20
2    1e+20
3    1e+20
4    1e+20
5    1e+20
6    1e+20
7    1e+20
8    1e+20
9    1e+20
10   1e+20
11   1e+20
12   1e+20
13   1e+20
14   1e+20
15   1e+20
16   1e+20
17   1e+20
18   1e+20
19   1e+20
20   1e+20
21   1e+20
22   1e+20
23   1e+20
24   1e+20
25   1e+20
26   1e+20
27   1e+20
28       0.390913
29   1e+20
30   1e+20
31   1e+20
32   1e+20
33       0.0450003
34   1e+20
35   1e+20
36   1e+20
37   1e+20
38   1e+20
39   1e+20
```

```
40   1e+20
41   1e+20
42   1e+20
43      21.8687
44   1e+20
45   1e+20
46   1e+20
47   1e+20
48       0.921014
49       0.240039
50   1e+20
51   1e+20
52   1e+20
53   1e+20
54   1e+20
55   1e+20
56       0.418821
57      37.0219
58   1e+20
59   1e+20
60   1e+20
61       1.57214
62       1.04864
63       0.230967
;

ampl: display _conname, _con, _con.slack, _con.up, _con.current, _con.down;
:          _conname              _con       _con.slack      _con.up       :=
1    Total_Demand_42           1.64179           0          925081
2    Total_Demand_32           1.48808           0          535557
3    'Max_Demand_ODM[1]'       0              6e+05          1e+20
4    'Max_Demand_ODM[2]'       0              6e+05          1e+20
5    'Max_Demand_ODM[3]'       0              6e+05          1e+20
6    'Max_Demand_ODM[4]'       0             372000          1e+20
7    'Max_Demand_ODM[5]'       0             508000          1e+20
8    'Max_Demand_ODM[6]'       0              6e+05          1e+20
9    'Max_Demand_ODM[7]'      -0.134395          0          673132
10   'Max_Demand_ODM[8]'       0             342375          1e+20
11   'Max_Demand_ODM[9]'       0             327625          1e+20
12   Shipping_Demand_Air_42   23.0413            0           50708.1
13   Shipping_Demand_Air_32   37.9177            0           58090.9
14   Shipping_Demand_Road_42   0.259806          0          104098
15   Shipping_Demand_Road_32   1.42275           0          126515
16   Shipping_Demand_Rail_42   0.368084          0          290719
17   Shipping_Demand_Rail_32   0.583631          0          126067
18   Cost                     -0.000641203       0      3344320000
;
:    _con.current    _con.down      :=
1    920000            898319
2    530000            508287
3     6e+05                 0
4     6e+05                 0
5     6e+05                 0
6     6e+05            228000
7     6e+05             92000
8     6e+05                 0
9     6e+05            287938
10    6e+05            257625
11    6e+05            272375
12    46000             25909.9
```

```
13    53000             29275.9
14    92000             40375.2
15    79500                 0
16   138000                 0
17    79500                 0
18        3.3e+09   3289610000
;

ampl:
```

Output for CNY 3B Budget:

```
ampl: option solver cplex;
ampl: option cplex_options 'sensitivity';
ampl: option presolve 0;
ampl: model project.mod;
ampl: data project.dat;
ampl: solve;
CPLEX 12.10.0.0: sensitivity
CPLEX 12.10.0.0: optimal solution; objective 7401248.178
24 dual simplex iterations (0 in phase I)

suffix up OUT;
suffix down OUT;
suffix current OUT;
ampl: display _varname, _var, _var.rc, _var.down, _var.current, _var.up;
:     _varname      _var        _var.rc          _var.down    _var.current
 :=
1    'ODM[1,1]'       0         11.2863           68.1671     79.4534
2    'ODM[1,2]'       0         18.4141           61.0394     79.4534
3    'ODM[1,3]'       0          1.49683           1.88545     3.38229
4    'ODM[1,4]'       0          0.427667         2.95462     3.38229
5    'ODM[1,5]'   90305.7        0                3.35259     3.38229
6    'ODM[1,6]'       0          0.169334         1.40318     1.57252
7    'ODM[1,7]'  229694          0               -2.60397     0.386232
8    'ODM[2,1]'       0         51.6678          -2.46873    49.199
9    'ODM[2,2]'       0         64.4978         -15.2987     49.199
10   'ODM[2,3]'       0         14.8204         -12.7261      2.09438
11   'ODM[2,4]'       0         13.3949         -11.3005      2.09438
12   'ODM[2,5]'       0         13.2523         -11.1579      2.09438
13   'ODM[2,6]'       0         14.8948         -13.9211      0.973731
14   'ODM[2,7]'       0         13.0389         -12.7997      0.239162
15   'ODM[3,1]'       0         48.453           -4.73464    43.7184
16   'ODM[3,2]'       0         59.8575         -16.1391     43.7184
17   'ODM[3,3]'       0         31.1086         -29.2475      1.86107
18   'ODM[3,4]'       0         29.683          -27.822       1.86107
19   'ODM[3,5]'       0         29.5405         -27.6794      1.86107
20   'ODM[3,6]'       0         31.3078         -30.4426      0.86526
21   'ODM[3,7]'       0         30.1752         -29.9627      0.21252
22   'ODM[4,1]'   46000          0              -67.5254     68.112
23   'ODM[4,2]'       0          7.12778          60.9842    68.112
24   'ODM[4,3]'       0          1.06917          1.83032     2.89949
25   'ODM[4,4]'       0          0.0712778        2.82821     2.89949
26   'ODM[4,5]'    1694.3        0             -1e+20         2.89949
27   'ODM[4,6]'  138000          0               -0.9519      1.34805
28   'ODM[4,7]'  414306          0                0.301649    0.3311
29   'ODM[5,1]'       0     3652330          -3652330         0.9504
30   'ODM[5,2]'       0     3652330          -3652330         0.9504
31   'ODM[5,3]'       0         38.6239         -38.5835      0.040458
32   'ODM[5,4]'       0         37.9112         -37.8707      0.040458
33   'ODM[5,5]'       0         37.5548         -37.5143      0.040458
34   'ODM[5,6]'       0     3652460          -3652460         0.01881
35   'ODM[5,7]'       0     3652470          -3652470         0.00462
36   'ODM[6,1]'       0         68.3906         -46.5314     21.8592
37   'ODM[6,2]'       0         82.6461         -60.7869     21.8592
38   'ODM[6,3]'       0     3652460          -3652460         0.930534
39   'ODM[6,4]'       0     3652460          -3652460         0.930534
40   'ODM[6,5]'       0     3652460          -3652460         0.930534
41   'ODM[6,6]'       0     3652460          -3652460         0.43263
42   'ODM[6,7]'       0         36.3693         -36.2631      0.10626
43   'ODM[7,1]'       0          3.46585         18.2666     21.7325
44   'ODM[7,2]'       0         14.1575           7.57496    21.7325
```

```
45   'ODM[7,3]'       0        7.17139       -6.24625     0.92514
46   'ODM[7,4]'       0        5.74583       -4.8207      0.92514
47   'ODM[7,5]'       0        5.46072       -4.53558     0.92514
48   'ODM[7,6]'       0        7.9427        -7.51258     0.430122
49   'ODM[7,7]'       0        6.49684       -6.3912      0.105644
50   'ODM[8,1]'   53000        0            -50.6027     59.5901
51   'ODM[8,2]'       0        5.34583       54.2442     59.5901
52   'ODM[8,3]'       0        1.12263        1.41409     2.53672
53   'ODM[8,4]'       0        0.32075        2.21597     2.53672
54   'ODM[8,5]'   79500        0             -1.1537      2.53672
55   'ODM[8,6]'   79500        0             -0.672576    1.17939
56   'ODM[8,7]'  318000        0          -1e+20          0.289674
57   'ODM[9,1]'       0       29.051          7.84827    36.8993
58   'ODM[9,2]'       0       38.6735        -1.77423    36.8993
59   'ODM[9,3]'       0        9.88023       -8.30945     1.57078
60   'ODM[9,4]'       0        8.81107       -7.24029     1.57078
61   'ODM[9,5]'       0        8.70415       -7.13337     1.57078
62   'ODM[9,6]'       0        9.80904       -9.07874     0.730298
63   'ODM[9,7]'       0        8.54407       -8.3647      0.179372
;
:     _var.up      :=
1    1e+20
2    1e+20
3    1e+20
4    1e+20
5    1e+20
6    1e+20
7        0.415683
8    1e+20
9    1e+20
10   1e+20
11   1e+20
12   1e+20
13   1e+20
14   1e+20
15   1e+20
16   1e+20
17   1e+20
18   1e+20
19   1e+20
20   1e+20
21   1e+20
22     71.5778
23   1e+20
24   1e+20
25   1e+20
26       2.92919
27       1.51738
28       3.3213
29   1e+20
30   1e+20
31   1e+20
32   1e+20
33   1e+20
34   1e+20
35   1e+20
36   1e+20
37   1e+20
38   1e+20
39   1e+20
```

```
40   1e+20
41   1e+20
42   1e+20
43   1e+20
44   1e+20
45   1e+20
46   1e+20
47   1e+20
48   1e+20
49   1e+20
50      64.9359
51   1e+20
52   1e+20
53   1e+20
54       2.85747
55      10.9884
56       2.14164
57   1e+20
58   1e+20
59   1e+20
60   1e+20
61   1e+20
62   1e+20
63   1e+20
;

ampl: display _conname, _con, _con.slack, _con.up, _con.current, _con.down;
# $5 = _con.current
:          _conname              _con     _con.slack     _con.up        $5
 :=
1    Total_Demand_42          103.59             0        920007     920000
2    Total_Demand_32           94.3174           0        530008     530000
3    'Max_Demand_ODM[1]'        0           280000         1e+20      6e+05
4    'Max_Demand_ODM[2]'        0            6e+05         1e+20      6e+05
5    'Max_Demand_ODM[3]'        0            6e+05         1e+20      6e+05
6    'Max_Demand_ODM[4]'       -0.422388         0        705160      6e+05
7    'Max_Demand_ODM[5]'        0            6e+05         1e+20      6e+05
8    'Max_Demand_ODM[6]'        0            6e+05         1e+20      6e+05
9    'Max_Demand_ODM[7]'        0            6e+05         1e+20      6e+05
10   'Max_Demand_ODM[8]'        0            70000         1e+20      6e+05
11   'Max_Demand_ODM[9]'        0            6e+05         1e+20      6e+05
12   Shipping_Demand_Air_42   135.637            0       46010.7      46000
13   Shipping_Demand_Air_32   110.193            0       53014.2      53000
14   Shipping_Demand_Road_42    4.92056          0       92376.5      92000
15   Shipping_Demand_Road_32    3.69042          0        80002       79500
16   Shipping_Demand_Rail_42    2.29995          0        138565     138000
17   Shipping_Demand_Rail_32    1.85196          0        80253       79500
18   Cost                      -0.050309         0    3000770000      3e+09
;
:    _con.down      :=
1        919626
2        529589
3        320000
4             0
5             0
6        598027
7             0
8             0
9             0
10       530000


11            0
12         45430.8
13         52241.1
14         75580.8
15         52742.8
16       107898
17         39364.1
18   2999990000
;

ampl:
```

```
var ODM {j in 1..9, i in 1..7} >=0;
#first parameter is ODM location, second is shipping method, note for j 8 and 9 they are 32" LCD
for ODM 1 and 2 respectively

param co2{i in 1..7};
param distance{j in 1..9};
param prod_cost{j in 1..9};
param ship_cost{j in 1..9, i in 1..7};


minimize CO2: sum {i in 1..7, j in 1..7} 0.022 * co2[i] * distance[j] * ODM[j,i] + sum {i in
1..7, j in 8..9} 0.0165 * co2[i] * distance[j] * ODM[j,i];

subject to
    Total_Demand_42: sum {j in 1..7, i in 1..7} ODM[j,i] = 920000;
    Total_Demand_32: sum {j in 8..9, i in 1..7} ODM[j,i] = 530000;
    Max_Demand_ODM {j in 1..9}: sum{i in 1..7} ODM[j,i] <= 600000;
    Shipping_Demand_Air_42: sum {j in 1..7, i in 1..2} ODM[j,i] >= 46000;
    Shipping_Demand_Air_32: sum {j in 8..9, i in 1..2} ODM[j,i] >= 53000;
    Shipping_Demand_Road_42: sum {j in 1..7, i in 3..5} ODM[j,i] >= 92000;
    Shipping_Demand_Road_32: sum {j in 8..9, i in 3..5} ODM[j,i] >= 79500;
    Shipping_Demand_Rail_42: sum {j in 1..7} ODM[j,6] >= 138000;
    Shipping_Demand_Rail_32: sum {j in 8..9} ODM[j,6] >= 79500;
    Cost: sum{j in 1..7, i in 1..7} (prod_cost[j] + ship_cost[j,i]*0.022)* ODM[j,i] + sum{j in
8..9, i in 1..7} (prod_cost[j] + ship_cost[j,i] * 0.0165)* ODM[j,i] <= 3300000000;
```

```
param co2 :=
1 1.44
2 1.44
3 0.0613
4 0.0613
5 0.0613
6 0.0285
7 0.007;

param distance :=
1 2508
2 1553
3 1380
4 2150
5 30
6 690
7 686
8 2508
9 1553;

param prod_cost :=
1 1983.4
2 2254
3 2582.4
4 1976.1
5 2711.3
6 2704.8
7 2125.2
8 1818.0
9 1996.4;

param ship_cost :=
1 1 64400
1 2 70840
1 3 6182.4
1 4 5216.4
1 5 4830
1 6 4250.4
1 7 3091.2
2 1 115920
2 2 127512
2 3 7084
2 4 5796
2 5 5667.2
2 6 5796
2 7 2704.8
3 1 103040
3 2 113344
3 3 7084
3 4 5796
3 5 5667.2
3 6 5796
3 7 3284.4
4 1 64400
4 2 70840
4 3 6182.4
4 4 5280.8
4 5 5216.4
```

```
4 6 4250.4
4 7 3091.2
5 1 3300000000
5 2 3300000000
5 3 9660
5 4 9016
5 5 8694
5 6 3300000000
5 7 3300000000
6 1 135240
6 2 148120
6 3 3300000000
6 4 3300000000
6 5 3300000000
6 6 3300000000
6 7 3413.2
7 1 103040
7 2 112700
7 3 7084
7 4 5796
7 5 5538.4
7 6 5860.4
7 7 2769.2
8 1 64400
8 2 70840
8 3 6182.4
8 4 5216.4
8 5 4830
8 6 4250.4
8 7 3091.2
9 1 115920
9 2 127512
9 3 7084
9 4 5796
9 5 5667.2
9 6 5796
9 7 2704.8;
```