INDENG 162 Project

DHL Case Study

Fall 2020

By: Jonathan Brian, Kezia Liman, Timotius Vincent, Vincent Angelo

Contents

1. Abstract

Logistics company Deutsche Post DHL partnered with a consumer electronic company (CEC) to handle logistics distribution for their industry-leading 32” and 42” LCD TVs. Multiple original design manufacturers (ODMs) in China and Taiwan were subcontracted to manufacture these products, before they were delivered to a distribution center in Shanghai. With an initial budget of CNY 3B, DHL managed production outputs from 7 ODMs and multiple transportation methods to fulfill the order for 530,000 and 920,000 units of the 32” and 42” TVs respectively.

Nonetheless, as part of the ‘Go Green’ environmental protection initiative, DHL was determined to reduce its CO2 emissions by 30% compared to the 2007 baseline of 7.36M kg of CO2 per Ton-KM shipped. This is supported by assumed government legislation that awarded efforts to reduce emissions through tax incentives. Also, customer awareness of DHL’s ‘Go Green’ initiative would most likely inflate its brand value, further increasing the budget allocated to supply-chain management. Assuming an updated budget ceiling of CNY 3.3B, this report aims to estimate corresponding reductions in CO2 emission and provide recommendations on how to achieve the aforementioned 30% reduction.

2. Solutions and Recommendations

According to our calculations as displayed in Table 3, a budget of CNY 3.1B would decrease CO2 emissions by roughly 34%, achieving the previously stated goal of a 30% carbon reduction. This means that with a budget of CNY 3.3B, DHL could reinvest the remaining ~CNY 200M to researching alternative transportation routes and infrastructure that could further decrease

CO2 emissions. Nonetheless, assuming DHL aims for higher carbon reductions, an investment of CNY 3.2B reduces CO2 emissions by 52.16%, while a higher investment of CNY 3.25B reduces CO2 emissions by 52.69% and CNY 3.3B reduces emissions by 52.99%. As such, if DHL spends the entire CNY 3.3B budget, carbon reductions are only marginally better than if DHL spends CNY 3.2B – more specifically, only 0.83% better with an additional 100M investment. In conclusion, spending any more than CNY 3.2B only contributes to fractional improvements in carbon reductions – sub-optimal fiscal spending that is considered as wasted opportunity cost. The extra CNY 100M would only reduce CO2 emissions by less than 1%, and DHL could be better off spending that remaining budget on research and other investments that lead to more efficient, eco-friendly transportation methods.

We also found that the quantity demanded of each item affects CO2 emission – if consumers switch over to smaller, lighter LCDs, carbon emissions will decrease. For instance, since the 32" TV is lighter than the 42", switching to the smaller 32” maintains cost, but reduces emissions. This also applies to the manufacturers in designing thinner, lighter LCDs. Another factor leading to a decrease in CO2 emissions would be flexibility in inventory levels. If DHL could ship all LCDs through land, the process would emit less CO2 emissions, but shipment times would unfortunately suffer. This trade-off is a factor that should be considered in prioritizing carbon emissions over shipment durations.

3. LP Model

3.1. Limitations/Assumptions, Decision Variables

Before any variables are defined, there are several limitations and assumptions associated with the LP. Each ODM delivers TVs through 7 different methods, namely {Regular Air, Express Air, Road, Road LTL, Road-Network, Rail and Water}. We can subdivide them into 4 main categories: Air Transportation, Land Transportation, Rail Transportation, and Water Transportation. Since delivery times for each transportation method range from 2 days (by air) to 10 days (by water), there is a minimum product amount associated with each transportation method to maintain a satisfactory inventory level. Also, due to geographical constraints, products from ODM 5 can only be delivered through Land Transportation while products from ODM 6 can only be delivered through Air and Water Transportation. 32” LCD TVs are also produced exclusively by ODMs 1 and 2.

Regarding production output, a total of 920,000 units of LCD 42” and 530,000 units of LCD 32” must be supplied to the distribution center. Following that, production from each ODM is also controlled between 200,000 - 600,000. Since there are 7 ODMs each with a minimum production of 200,000 units, adding them up results in a total of 1,400,000 units (7 x 200,000). However, the demand for the 42” LCD is 920,000 units. Therefore, there must be ODMs that produce units below the predetermined minimum units. Assuming that ordering below the minimum would prevent each ODM from enjoying economies of scale, resulting in an increase in cost, DHL wouldn’t subcontract from all the ODMs. Hence, either at least 200,000 is subtracted from a certain ODM or none at all. A maximum number of productions is also set to prevent the chance of dependency.

This LP also assumes two implicit conditions: the costs and ODM production minimum/maximum are kept at a constant. Also, there are no unforeseen circumstances that could cause delay/cancellation of delivery or increases in cost.

The decision variables used in LP are as follows:

1. $X_{ij} \geq 0;\ i, j \in \{1,2,3,4,5,6,7\}$: number of 42" LCD TVs produced by ODM i using transportation method j. All ODMs i can produce 42" TVs using all transportation methods j $\in$ {1,2,3,4,5,6,7} corresponding to {Regular Air, Air Express, Road, Road LTL, Road-Network, Rail, Water}.

2. $Y_{ij} \geq 0;\ i \in \{1,2\}, j \in \{1,2,3,4,5,6,7\}$: number of 32" LCD TVs produced by ODM i using transportation method j. Only ODMs $i \in \{1,2\}$ can produce 32" TVs using all transportation methods $j \in \{1,2,3,4,5,6,7\}$.

3. $Z_{ij} \in \{0, 1\}$. Z is a binary variable which can only take two values {0,1}. This is a helper variable to allow DHL to either purchase from a particular ODM with minimum order 200,000 and maximum order 600,000 or none at all. If Z_{ij} = 1, then DHL will purchase product i, where product 1 = LCD42" and product 2 = LCD32", from ODM j $\in \{1,2,3,4,5,6,7\}$. If Z_{ij} = 0, DHL won't purchase any product i from ODM j.

4. All variables have a non-negativity constraint, as it is not possible to produce a negative product.

3.2. Objective Function, Constraints

This problem can be formulated as a linear program, in which the objective is to minimize CO2 emissions. Mathematically this can be represented as

$$Min \sum_{i=1}^{7}\sum_{j=1}^{7} E_{ij} \times X_{ij} + \sum_{i=1}^{2}\sum_{j=1}^{7} E_{ij} \times Y_{ij}$$

where E_{ij} corresponds to the CO2 Emission in Kg/Ton – Km *(provided in Table 1).* We separated X_{ij} with Y_{ij} because different LCDs have different weights, hence different proportions of CO2 were emitted.

The minimum amount of 42" LCD TVs for each group of transportation method Air, Rail, Road are 42000, 92000, and 138000 respectively. Mathematically, 42" LCD by air can be represented as $\sum_{i=1}^{7}\sum_{j=1}^{2} X_{ij} \geq 46000$ as air transportation includes Regular Air (j=1) and Express Air (j=2). Similarly, constraints for 42" LCD by road are given by $\sum_{i=1}^{7}\sum_{j=3}^{5} X_{ij} \geq 92000$, and 42" LCD by rail = $\sum_{i=1}^{7} X_{i5} \geq 138000$. There are no constraints for water transportation. The 32" LCDs also have different minimum units to be shipped by each group of transportation: 53000 for Air, 79500 for Road, and 79500 for Rail. Mathematically these are represented as $\sum_{i=1}^{2}\sum_{j=1}^{2} Y_{ij} \geq 53000$, $\sum_{i=1}^{2}\sum_{j=3}^{5} Y_{ij} \geq 79500$, $\sum_{i=1}^{7} Y_{i5} \geq 79500$.

For geographical constraints, we know that ODM 5 can only be shipped through Road. This is the same as saying all other shipping methods except Road, Road LTL, and Road Network have a common value of zero ($X_{5,1} + X_{5,2} + X_{5,6} + X_{5,7} = 0$). As each variable is constrained to be non-negative (>= 0), the only way the sum is 0 is if all variables in that sum equal to 0. Similarly, ODM6 can only ship through air and water, so we make all road and rail methods equal to 0 ($X_{6,3} + X_{6,4} + X_{6,5} + X_{6,6} = 0$).

Additionally, each ODM should at least supply at least 200,000 units or none. For 42" LCDs, this can be represented as $\sum_{j=1}^{7} X_{ij} \geq 200{,}000 \times Z_{1,i}$ for each $i \in \{1,2,3,4,5,6,7\}$. Each ODM should also supply at most 600,000 units. For 42" LCD this can be represented as $\sum_{j=1}^{7} X_{ij} \leq 600{,}000 \times Z_{1,i}$ for $i \in \{1,2,3,4,5,6,7\}$. Notice that the lower bound and upper bound is multiplied by the same variable $Z_{1,i}$. This way if $Z_{1,i}$ = 0, LB will be >= 0 and UB will be <= 0, meaning ODM *i* will ship 0 unit. Likewise, 32" LCD can be represented with the same formulation with a slight modification. Lower bound will become $\sum_{j=1}^{7} Y_{ij} \geq 200{,}000 \times Z_{2,i}$ and upper bound will become $\sum_{j=1}^{7} Y_{ij} \leq 600{,}000 \times Z_{2,i}$ for each $i \in \{1,2\}$.

The distribution center also has specific demands for 42" LCD and 32" LCD. This can be represented mathematically as $\sum_{i=1}^{7}\sum_{j=1}^{7} X_{ij} = 920{,}000$ for 42" LCD and $\sum_{i=1}^{2}\sum_{j=1}^{7} Y_{ij} = 530{,}000$ for 32" LCD. Since X_{ij} represents unit shipped by each ODM through each transportation method, the sum of all X_{ij} will be the total 42" LCD shipped to the distribution center.

Lastly, we are limited by a budget constraint of CNY 3.3 billion, where the shipping cost from each ODM through each transportation method and for each LCD size varies. Total cost which is shipping cost + production cost can be seen in *Table 2*. Mathematically, this is represented as

$$\sum_{i=1}^{7}\sum_{j=1}^{7} C_{ij} \times X_{ij} + \sum_{i=1}^{2}\sum_{j=1}^{7} C_{ij} \times Y_{ij} \leq 3{,}300{,}000{,}000$$

where C_{ij} corresponds to the total cost for each transportation method in CNY.

As a side note, DHL initially has a different objective, which is purely minimizing cost. In order to accurately calculate the decrease in CO2 emissions, we should compare the CO2 emitted when DHL aims to only minimize cost (with a CNY 3 billion budget) to the CO2 produced when DHL aims to minimize emissions (with a CNY 3.3 billion budget). This difference is calculated in

Table 3. The initial CO2 produced without taking into account any CO2 emissions can be calculated using the same linear program by slight modifications. The objective function will now be

$$Min \sum_{i=1}^{7} \sum_{j=1}^{7} C_{ij} \times X_{ij} + \sum_{i=1}^{2} \sum_{j=1}^{7} C_{ij} \times Y_{ij}$$

and we can add a helper variable E >= 0 and a helper constraint $\sum_{i=1}^{7} \sum_{j=1}^{7} E_{ij} \times X_{ij} + \sum_{i=1}^{2} \sum_{j=1}^{7} E_{ij} \times Y_{ij} = E$ to calculate the corresponding amount of CO2 emission.

3.3. AMPL Output

After running this linear program in AMPL, we found that the minimum budget to satisfy all various constraints is CNY 2,998,555,825. With this budget, a total of 920,000 42" LCD are purchased from only 2 different suppliers, ODM1 and ODM4 (this can also be seen by the *Zij* variable where for i = 1, only Z[1,1] and Z[1,4] = 1), 92,000 from ODM1 through Road-Network, 228,000 from ODM1 through water, 46,000 from ODM4 through Regular Air, 138,000 from ODM4 through Rail and 416,000 from ODM4 through water. We also purchase a total of 530,000 32" LCD from ODM1 only, where 53,000 is transported through Regular Air, 79,500 through Road-Network, 79,500 through Rail and 318,000 through Water. Here, we observe that when minimizing cost, we only use 4 out of the 7 total transportation methods (Regular Air, Road-Network, Rail, Water). Since there still is a minimum amount to be shipped using Air, Road, and Rail, even though the cost of shipping through them is higher than water, we still need to ship the minimum possible products through them. Regular Air and Air Express both are categorized into the same shipping method 'Air', so we would choose the cheapest method between the two. The same argument applies for Road, Road-LTL and Road-Network. This optimal solution minimizes our cost, with the amount of CO_2 being emitted equal to 7,401,970 kg.

When the focus of the company is no longer minimizing cost but minimizing CO_2 emissions *(Table 5)*, which is the goal of this study, we obtain different results. With a 10% increase in budget from CNY 3B to 3.3B, CO_2 emissions are significantly reduced by 3%. With this budget, we still purchase a total of 920,000 42” LCD from ODM4 but replace ODM 1 with ODM7. 320,000 from ODM4 through Water, 46,000 from ODM7 through Regular Air, 92,000 from ODM7 through Road-Network, 138,000 from ODM7 through Rail and 324,000 from ODM7 through Water. In contrast to the previous solution, all our 32” LCD will be purchased through ODM 2 where 53,000 are shipped through Regular Air, 79,500 through Road, 79,500 through Rail and 318,000 through Water. The change to subcontract production from ODM1 to ODM7 for 42” LCD derives from ODM7 being closer to our distribution center. Similarly, ODM2 is selected to produce 32” TVs because it is relatively closer than ODM1. Since CO_2 emissions are heavily dependent on distance, this plays an important role in choosing which ODM to subcontract from. Out of the CNY 3.3 billion budget allocated, we achieve optimal results by using CNY 3,270,940,000.

We can see that with a 10% increase in budget we got a 53% decrease in CO_2 emission. With this significant decrease, we decided to explore the relationship between budget and CO_2 emission when our objective is now minimizing CO_2. In *Table 3*, we can see the relationship between every CNY 50M increase in budget to reductions in CO_2 emissions. Interestingly, with the same budget (3 billion) but with a different objective, *Table 3* shows that CO_2 emission only decreases by 0.53%. It shows that when limited to a budget of 3B, both objectives yield similar objective values. Nonetheless, by increasing the budget to 3.05B (3.3% increase), we could significantly reduce emission by 18.75%. Plotting budget in the X axis and CO2 emission in the Y axis *(Graph 1)* we can see that the reduction in CO2 emissions with constant budget increments of CNY 50M exponentially decreases. Subsequently, we can also see from the graph that the reduction in CO2 emission is initially very steep. Up until an increase of 6.6% in budgets to around CNY 3.2B, CO2 emission decreased by 52.16%. Beginning from there, we can see that for every CNY 50M increase, the decrease is less than 1%.

If we remove the budget constraints in our linear program, we can see the minimum CO2 our shipment can emit while satisfying all constraints is 3293331.145 – a 55.51% decrease from the original emission levels. In order to achieve this level of emission reduction, the amount needed will be CNY 3,746,760,000, about 25% higher than the initial CNY 3B budget.

4. Technical Explanations of Recommendations:

4.1. Allocate a small percentage of the increased CNY 3.3B budget into researching alternative transportation or manufacturing methods that contribute to lower CO2 emissions with higher efficiencies, instead of spending the entire CNY 3.3B into optimizing current manufacturing/shipping systems.

According to the CNY 3.3B budget AMPL sensitivity output in *Table 4*, the 'Cost' constraint has a shadow price, displayed as variable 'con', of zero. A shadow price of zero indicates that within the constraint R.H.S. range of '_con.down' < 'Cost' < '_con.up', there is no change in the optimal objective value. As such, a reduction in budget spending from the existing budget ceiling '_con.current' = 3.3B to '_con.down' = 3270940000 (3.27B) maintains optimality of current basis without increasing the minimum CO2 emissions value. A surplus of over CNY 29M is hence left over, which can be invested into researching renewable, efficient alternatives of transportation or manufacturing processes that further reduce CO2 emissions.

4.2. Opportunity Cost of Increased Budget Spending

Graph 1 shows how the slope comes into a plateau after we increase budget by 6.6% (point x), where any increase in the budget from that point onwards still decreases CO2 emission, but at an exponentially slower rate. As the budget increases by 10%, which is a 4.4% increase from point x, CO2 only decreases by less than 1%. Furthermore, we can keep increasing our budget by 25% and reach the minimum CO2 emission. But with this 25% increase in budget, we merely reduce the emission by about 3-4% from point x. From a business point of view, this can be disadvantageous, since it disregards the opportunity cost. The 18.4% increase in budget (from point x) could be used in other resources which could in return yield greater utility and profit to DHL. It is thus more rational to only allocate a portion of the potential CNY 3.3B budget to minimize CO2 and use the remaining budget for other investments than using the entire 3.3B budget.

4.3. Flexibility in Quantity Demanded

Looking at *Table 4,* we can see that the shadow price for 42" LCD Demand is 0.3311. Hence, if demand for 42" LCD decreases to 800,000 units (con_down) or even increases to 932,214 units (con_up), the optimal solution would remain the same, but CO2 emission would change by $0.3311 \times \Delta(number\ of\ units)$. If the new demand is higher, then CO2 emission will increase by that respective amount and vice versa. Likewise, the shadow price for 32" LCD demand is 0.179372. If demand for 32” LCD decreases to 212,000 units (con_down) or increases to 544,236 units (con_up), the optimal solution would remain the same, but CO_2 emission would change by 0.179372 × the number of units. Nonetheless, it is interesting to note that within the range above, any change in quantity demanded has no effect on the optimal solution in *Table 5*. The equal number of units would still be transported from the same ODMs through the same transportation method, allowing some degree of flexibility in demand without recalculation.

4.4. Flexibility in Inventory Level

From *Table 4*, the first 6 constraints correspond to the minimum number of 32” and 42” LCD TVs DHL should ship to meet the predetermined inventory requirements. Each of these constraints has _con > 0, meaning the minimum unit required for each transportation method affects the CO_2 emission. We can also see that if there is a change in any underlying circumstances, such as infrastructure development that would affect road traffic on DHL’s current route (Land transportation might for some time take longer days), this could affect the minimum unit for other methods of transportation like air/rail. In this case, we wouldn’t need to recalculate our linear program as our optimal solution in *Table 5* would remain optimal if the minimum requirement for LCD 42” by Air, Road, Rail changes to 59171.4, 416000, 462000 respectively and if the minimum requirement for LCD 32” by Air, Rail, Road changes to 68554, 397500, 397500 respectively. The optimal value however does change by multiplying the respective _con value with the increase in units.

5. Conclusion

CO2 emissions vastly alter DHL's planning in terms of logistics distribution and management. This can be seen from the change in the chosen ODMs, subcontractors, as well as the methods of transportation. Nonetheless, benefits from undertaking this 'Go Green' initiative stretch from taking care of the environment to various business opportunities and tax incentives. In addition, the budget allocated can be appropriately used for investments in other areas of the business, further increasing DHL's profits in the long run.

	CO2 Emission in Kg						
Product - ODM	Regular Air	Air Express	Road	Road LTL	Road-Network	Rail	Water
LCD42" ODM1	79.4534	79.4534	3.3823	3.3823	3.3823	1.5725	0.3862
LCD42" ODM2	49.1990	49.1990	2.0944	2.0944	2.0944	0.9737	0.2392
LCD42" ODM3	43.7184	43.7184	1.8611	1.8611	1.8611	0.8653	0.2125
LCD42" ODM4	68.1120	68.1120	2.8995	2.8995	2.8995	1.3481	0.3311
LCD42" ODM5	-	-	0.0405	0.0405	0.0405	-	-
LCD42" ODM6	21.8592	21.8592	-	-	-	-	0.1063
LCD42" ODM7	21.7325	21.7325	0.9251	0.9251	0.9251	0.4301	0.1056
LCD32" ODM1	59.5901	59.5901	2.5367	2.5367	2.5367	1.1794	0.2897
LCD32" ODM2	36.8993	36.8993	1.5708	1.5708	1.5708	0.7303	0.1794

Table 1: CO2 Emissions (in kg)

	Cost per Unit						
Product - ODM	Regular Air	Air Express	Road	Road LTL	Road-Network	Rail	Water
LCD42" ODM1	$ 3,400.20	$ 3,541.88	$ 2,119.41	$ 2,098.16	$ 2,089.66	$ 2,076.91	$ 2,051.41
LCD42" ODM2	$ 4,804.24	$ 5,059.26	$ 2,409.85	$ 2,381.51	$ 2,378.68	$ 2,381.51	$ 2,313.51
LCD42" ODM3	$ 4,849.28	$ 5,075.97	$ 2,738.25	$ 2,709.91	$ 2,707.08	$ 2,709.91	$ 2,654.66
LCD42" ODM4	$ 3,392.90	$ 3,534.58	$ 2,112.11	$ 2,092.28	$ 2,090.86	$ 2,069.61	$ 2,044.11
LCD42" ODM5	$ -	$ -	$ 2,923.82	$ 2,909.65	$ 2,902.57	$ -	$ -
LCD42" ODM6	$ 5,680.08	$ 5,963.44	$ -	$ -	$ -	$ -	$ 2,779.89
LCD42" ODM7	$ 4,392.08	$ 4,604.60	$ 2,281.05	$ 2,252.71	$ 2,247.04	$ 2,254.13	$ 2,186.12
LCD32" ODM1	$ 2,880.60	$ 2,986.86	$ 1,920.01	$ 1,904.07	$ 1,897.70	$ 1,888.13	$ 1,869.00
LCD32" ODM2	$ 3,909.08	$ 4,100.35	$ 2,113.29	$ 2,092.03	$ 2,089.91	$ 2,092.03	$ 2,041.03

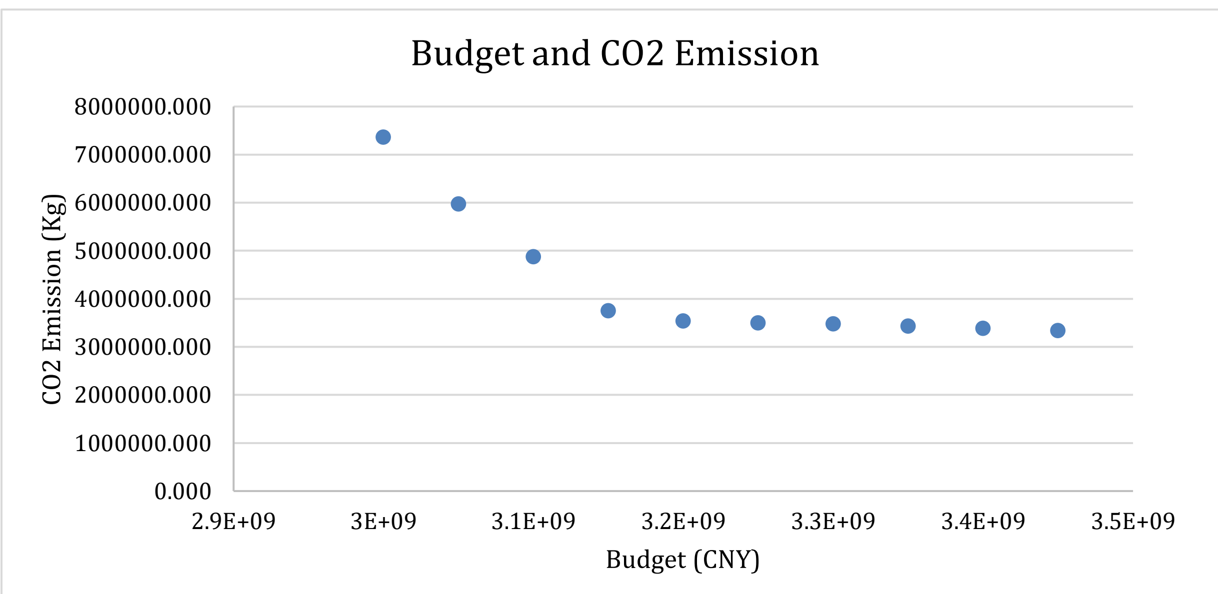
Table 2: Cost per Unit Production + Shipping (CNY)

Budget	CO2 Emission	Percent Decrease
3000000000	7362627.428	0.53%
3050000000	5974455.742	19.29%
3100000000	4875900.460	34.13%
3150000000	3749732.008	49.34%
3200000000	3540839.359	52.16%
3250000000	3502042.760	52.69%
3300000000	3479982.260	52.99%
3350000000	3432857.761	53.62%
3400000000	3385762.489	54.26%
3450000000	3337260.599	54.91%

Table 3: Comparison between Budget Increases and Percent Decrease of CO_2 Emission

```
ampl: display _conname, _con, _con.up, _con.current, _con.down;
:       _conname          _con         _con.up      _con.current    _con.down
 :=
1    MinimAir42       21.6268         59171.4    46000                  0
2    MinimRoad42       0.819496       416000     92000                  0
3    MinimRail42       0.324478       462000    138000                  0
4    MinimAir32       36.7199          68554     53000                  0
5    MinimRoad32       1.39141        397500     79500                  0
6    MinimRail32       0.550927       397500     79500                  0
7    limitTransODM5   -20.8478             0         0                  0
8    limitTransODM6   -0.925756            0         0                  0
9    SupplyLBODM142    0                   0         0             -1e+20
10   SupplyLBODM132    0                   0         0             -1e+20
11   SupplyUBODM142    0               1e+20         0                  0
12   SupplyUBODM132    0               1e+20         0                  0
13   SupplyLBODM242    0                   0         0             -1e+20
14   SupplyLBODM232    0              330000         0             -1e+20
15   SupplyUBODM242   -0.091938       107853         0                  0
16   SupplyUBODM232    0               1e+20         0             -70000
17   SupplyLBODM3      0                   0         0             -1e+20
18   SupplyUBODM3     -0.11858         47589.2       0                  0
19   SupplyLBODM4      0              120000         0             -1e+20
20   SupplyUBODM4      0               1e+20         0            -280000
21   SupplyLBODM5      0                   0         0             -1e+20
22   SupplyUBODM5     -1.11014         35486         0                  0
23   SupplyLBODM6      0                   0         0             -1e+20
24   SupplyUBODM6     -0.22484         39489.5       0                  0
25   SupplyLBODM7      0                4e+05        0             -1e+20
26   SupplyUBODM7     -0.225456       120000         0            -280000
27   DemandDC42        0.3311         934214    920000               8e+05
28   DemandDC32        0.179372       544236    530000             212000
29   Cost              0               1e+20          3.3e+09   3270940000
30   TotalCost         0          3270940000         0             -1e+20
;
```

Table 4: Model Sensitivity Output for CNY 3.3B Budget



Graph 1: Graph of Budget (in CNY) against CO_2 Emissions (in KG)

:	_varname	_var	_var.rc	_var.up	$5	_var.down
:=						
1	'X[1,1]'	0	57.4955	1e+20	79.4534	21.9579
2	'X[1,2]'	0	57.4955	1e+20	79.4534	21.9579
3	'X[1,3]'	0	2.23169	1e+20	3.38229	1.1506
4	'X[1,4]'	0	2.23169	1e+20	3.38229	1.1506
5	'X[1,5]'	0	2.23169	1e+20	3.38229	1.1506
6	'X[1,6]'	0	0.916938	1e+20	1.57252	0.655578
7	'X[1,7]'	0	0.055132	1e+20	0.386232	0.3311
8	'X[2,1]'	0	27.333	1e+20	49.199	21.866
9	'X[2,2]'	0	27.333	1e+20	49.199	21.866
10	'X[2,3]'	0	1.03572	1e+20	2.09438	1.05866
11	'X[2,4]'	0	1.03572	1e+20	2.09438	1.05866
12	'X[2,5]'	0	1.03572	1e+20	2.09438	1.05866
13	'X[2,6]'	0	0.410091	1e+20	0.973731	0.56364
14	'X[2,7]'	0	0	0.3311	0.239162	-1e+20
15	'X[3,1]'	0	21.879	1e+20	43.7184	21.8394
16	'X[3,2]'	0	21.879	1e+20	43.7184	21.8394
17	'X[3,3]'	0	0.829052	1e+20	1.86107	1.03202
18	'X[3,4]'	0	0.829052	1e+20	1.86107	1.03202
19	'X[3,5]'	0	0.829052	1e+20	1.86107	1.03202
20	'X[3,6]'	0	0.328262	1e+20	0.86526	0.536998
21	'X[3,7]'	0	0	0.3311	0.21252	-1e+20
22	'X[4,1]'	0	46.1541	1e+20	68.112	21.9579
23	'X[4,2]'	0	46.1541	1e+20	68.112	21.9579
24	'X[4,3]'	0	1.74889	1e+20	2.89949	1.1506
25	'X[4,4]'	0	1.74889	1e+20	2.89949	1.1506
26	'X[4,5]'	0	1.74889	1e+20	2.89949	1.1506
27	'X[4,6]'	0	0.692472	1e+20	1.34805	0.655578
28	'X[4,7]'	320000	0	0.386232	0.3311	0.239162
29	'X[5,1]'	0	1.05471e-15	1.05471e-15	0	-1e+20
30	'X[5,2]'	0	1.05471e-15	1e+20	0	-1.05471e-15
31	'X[5,3]'	0	-5.55112e-17	0.040458	0.040458	-1e+20
32	'X[5,4]'	0	-5.55112e-17	1e+20	0.040458	0.040458
33	'X[5,5]'	0	-5.55112e-17	1e+20	0.040458	0.040458
34	'X[5,6]'	0	21.3024	1e+20	0	-21.3024
35	'X[5,7]'	0	21.6268	1e+20	0	-21.6268
36	'X[6,1]'	0	0.126104	1e+20	21.8592	21.7331
37	'X[6,2]'	0	0.126104	1e+20	21.8592	21.7331
38	'X[6,3]'	0	5.55112e-17	5.55112e-17	0	-1e+20
39	'X[6,4]'	0	5.55112e-17	1e+20	0	-5.55112e-17
40	'X[6,5]'	0	5.55112e-17	1e+20	0	-5.55112e-17
41	'X[6,6]'	0	0.495018	1e+20	0	-0.495018
42	'X[6,7]'	0	0	0.232364	0.10626	-1e+20
43	'X[7,1]'	46000	-1.94289e-15	21.7325	21.7325	0.430122
44	'X[7,2]'	0	-1.94289e-15	1e+20	21.7325	21.7325
45	'X[7,3]'	0	5.55112e-17	1e+20	0.92514	0.92514
46	'X[7,4]'	0	5.55112e-17	1e+20	0.92514	0.92514
47	'X[7,5]'	92000	5.55112e-17	0.92514	0.92514	0.430122
48	'X[7,6]'	138000	-5.55112e-17	0.758384	0.430122	0.105644
49	'X[7,7]'	324000	0	0.3311	0.105644	-0.02046
50	'Y[1,1]'	0	22.6908	1e+20	59.5901	36.8993
51	'Y[1,2]'	0	22.6908	1e+20	59.5901	36.8993
52	'Y[1,3]'	0	0.965935	1e+20	2.53672	1.57078
53	'Y[1,4]'	0	0.965935	1e+20	2.53672	1.57078
54	'Y[1,5]'	0	0.965935	1e+20	2.53672	1.57078
55	'Y[1,6]'	0	0.449089	1e+20	1.17939	0.730298
56	'Y[1,7]'	0	0.110303	1e+20	0.289674	0.179372
57	'Y[2,1]'	53000	1.9984e-15	36.8993	36.8993	0.179372
58	'Y[2,2]'	0	1.9984e-15	1e+20	36.8993	36.8993
59	'Y[2,3]'	0	0	1e+20	1.57078	1.57078
60	'Y[2,4]'	0	0	1e+20	1.57078	1.57078
61	'Y[2,5]'	79500	0	1.57078	1.57078	0.179372
62	'Y[2,6]'	79500	0	1.17939	0.730298	0.179372
63	'Y[2,7]'	318000	0	0.289674	0.179372	-1e+20
64	'Z[1,1]'	0	0	1e+20	0	-1e+20
65	'Z[1,2]'	0	-55162.8	1e+20	0	-1e+20
66	'Z[1,3]'	0	-71148	1e+20	0	-1e+20
67	'Z[1,4]'	1	0	1e+20	0	-1e+20
68	'Z[1,5]'	0	-666083	1e+20	0	-1e+20
69	'Z[1,6]'	0	-134904	1e+20	0	-1e+20
70	'Z[1,7]'	1	-135274	1e+20	0	-1e+20
71	'Z[2,1]'	0	0	1e+20	0	-1e+20
72	'Z[2,2]'	1	0	1e+20	0	-1e+20
73	'Z[2,3]'	0	0	0	0	0
74	'Z[2,4]'	0	0	0	0	0
75	'Z[2,5]'	0	0	0	0	0
76	'Z[2,6]'	0	0	0	0	0
77	'Z[2,7]'	0	0	0	0	0

Table 5: AMPL Output

Appendix 1: AMPL Code

```
var X {i in 1..7, j in 1..7} >= 0;

var Y {i in 1..2, j in 1..7} >= 0;

var Z {i in 1..2, j in 1..7} binary;



minimize CO2:

(0.0165*2508)*(1.44 * (Y[1,1] + Y[1,2]) + 0.0613 * (Y[1,3] + Y[1,4] + Y[1,5]) +

0.0285 * Y[1,6] + 0.007 * Y[1,7]) +

(0.0165*1553)*(1.44 * (Y[2,1] + Y[2,2]) + 0.0613 * (Y[2,3] + Y[2,4] + Y[2,5]) +

0.0285 * Y[2,6] + 0.007 * Y[2,7]) +

(0.022*2508)*(1.44 * (X[1,1] + X[1,2]) + 0.0613 * (X[1,3] + X[1,4] + X[1,5]) +

0.0285 * X[1,6] + 0.007 * X[1,7]) +

(0.022*1553)*(1.44 * (X[2,1] + X[2,2]) + 0.0613 * (X[2,3] + X[2,4] + X[2,5]) +

0.0285 * X[2,6] + 0.007 * X[2,7]) +

(0.022*1380)*(1.44 * (X[3,1] + X[3,2]) + 0.0613 * (X[3,3] + X[3,4] + X[3,5]) +

0.0285 * X[3,6] + 0.007 * X[3,7]) +

(0.022*2150)*(1.44 * (X[4,1] + X[4,2]) + 0.0613 * (X[4,3] + X[4,4] + X[4,5]) +

0.0285 * X[4,6] + 0.007 * X[4,7]) +

(0.022*30)*(0.0613 * (X[5,3] + X[5,4] + X[5,5])) +

(0.022*690)*(1.44 * (X[6,1] + X[6,2]) + 0.007 * X[6,7]) +

(0.022*686)*(1.44 * (X[7,1] + X[7,2]) + 0.0613 * (X[7,3] + X[7,4] + X[7,5]) +

0.0285 * X[7,6] + 0.007 * X[7,7]);


subject to

MinimAir42: sum{i in 1..7, j in 1..2} X[i,j] >= 46000;

MinimRoad42: sum{i in 1..7, j in 3..5} X[i,j] >= 92000;
```

```
MinimRail42: sum{i in 1..7} X[i,6] >= 138000;

MinimAir32: sum{i in 1..2, j in 1..2} Y[i,j] >= 53000;
MinimRoad32: sum{i in 1..2, j in 3..5} Y[i,j] >= 79500;
MinimRail32: sum{i in 1..2} Y[i,6] >= 79500;

limitTransODM5: X[5,1] + X[5,2] + X[5,6] + X[5,7] = 0;
limitTransODM6: X[6,3] + X[6,4] + X[6,5] + X[6,6] = 0;

SupplyLBODM142: sum{j in 1..7} X[1,j] >= 200000 * Z[1,1];
SupplyLBODM132: sum{j in 1..7} Y[1,j] >= 200000 * Z[2,1];
SupplyUBODM142: sum{j in 1..7} X[1,j] <= 600000 * Z[1,1];
SupplyUBODM132: sum{j in 1..7} Y[1,j] <= 600000 * Z[2,1];

SupplyLBODM242: sum{j in 1..7} X[2,j] >= 200000 * Z[1,2];
SupplyLBODM232: sum{j in 1..7} Y[2,j] >= 200000 * Z[2,2];
SupplyUBODM242: sum{j in 1..7} X[2,j] <= 600000 * Z[1,2];
SupplyUBODM232: sum{j in 1..7} Y[2,j] <= 600000 * Z[2,2];

SupplyLBODM3: sum{j in 1..7} X[3,j] >= 200000 * Z[1,3];
SupplyUBODM3: sum{j in 1..7} X[3,j] <= 600000 * Z[1,3];

SupplyLBODM4: sum{j in 1..7} X[4,j] >= 200000 * Z[1,4];
SupplyUBODM4: sum{j in 1..7} X[4,j] <= 600000 * Z[1,4];

SupplyLBODM5: sum{j in 1..7} X[5,j] >= 200000 * Z[1,5];
SupplyUBODM5: sum{j in 1..7} X[5,j] <= 600000 * Z[1,5];
```

```
SupplyLBODM6: sum{j in 1..7} X[6,j] >= 200000 * Z[1,6];

SupplyUBODM6: sum{j in 1..7} X[6,j] <= 600000 * Z[1,6];


SupplyLBODM7: sum{j in 1..7} X[7,j] >= 200000 * Z[1,7];

SupplyUBODM7: sum{j in 1..7} X[7,j] <= 600000 * Z[1,7];


DemandDC42: sum{i in 1..7, j in 1..7} X[i,j] = 920000;

DemandDC32: sum{i in 1..2, j in 1..7} Y[i,j] = 530000;


Cost:

3400.2*X[1,1] + 3541.88*X[1,2] + 2119.41*X[1,3] + 2098.16*X[1,4] + 2089.66*X[1,5] + 2076.91*X[1,6] +

2051.41*X[1,7] + 4804.24*X[2,1] + 5059.26*X[2,2] + 2409.85*X[2,3] + 2381.51*X[2,4] + 2378.68*X[2,5] +

2381.51*X[2,6] + 2313.51*X[2,7] + 4849.28*X[3,1] + 5075.97*X[3,2] + 2738.25*X[3,3] +2709.91*X[3,4] +

2707.08*X[3,5] + 2709.91*X[3,6] + 2654.66*X[3,7] + 3392.9*X[4,1] + 3534.58*X[4,2] + 2112.11*X[4,3] +

2092.28*X[4,4] + 2090.86*X[4,5] + 2069.61*X[4,6] + 2044.11*X[4,7] + 2923.82*X[5,3] + 2909.65*X[5,4] +

2902.57*X[5,5] + 5680.08*X[6,1] + 5963.44*X[6,2] + 2779.89*X[6,7] + 4392.08*X[7,1] + 4604.6*X[7,2] +

2281.05*X[7,3] + 2252.71*X[7,4] + 2247.04*X[7,5] + 2254.13*X[7,6] + 2186.12*X[7,7] + 2880.6*Y[1,1] +

2986.86*Y[1,2] + 1920.01*Y[1,3] + 1904.07*Y[1,4] +

1879.7*Y[1,5] + 1888.13*Y[1,6] + 1869*Y[1,7] + 3909.08*Y[2,1] + 4100.35*Y[2,2] +

2113.29*Y[2,3] + 2092.03*Y[2,4] + 2089.91*Y[2,5] + 2092.03*Y[2,6]

+ 2041.03*Y[2,7] <= 3300000000;
```